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Complexity Management - A multiple case study analysis on control and reduction of complexity costs

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COMPLEXITY MANAGEMENT

A MULTIPLE CASE STUDY ANALYSIS ON CONTROL AND REDUCTION OF COMPLEXITY COSTS

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October 2016

Πάντα κατ' αριθμόν γίγνονται

- *Πυθαγόρας*

All is number

- *Pythagoras*

DECLARATION

This dissertation is the result of my own work and includes nothing, which is the outcome of work done in collaboration except where specifically indicated in the text. It has not been previously submitted, in part or whole, to any university of institution for any degree, diploma, or other qualification.

Signed:____

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ABSTRACT

Complexity tends to be arguably the biggest challenge of manufacturing companies. The motivation of further studying complexity is a combination between the existing literature and the practical experiences from the industry. Based on the latest trend companies are trying to supply a growing mix of products, with features more custom-made to cover individual needs, both regarding characteristics of products and support services. This necessity leads to a considerable increase of the complexity in the company, which affects the product portfolio, production and supply chain, market segments, IT systems, and business processes. In order to identify and eliminate complexity, several approaches are used, both by researchers and practitioners. The purpose of this thesis is to contribute to the existing knowledge of complexity management theory.

This research focuses on the relationship between product and process complexity. The possible factors for describing this correlation are identified and defined as complexity cost factors (CCFs). By identifying the CCFs this research intends to analyze the most relevant processes where the complexity and cost are directly related to the complexity of products. In this way, it will be possible to quantify the exact cost impact on those processes for each product variant. Furthermore, initiatives regarding complexity reduction are investigated. Standardization in product design, increased reusability of components, postponement of the customer order decoupling point (CODP) and utilization of configuration systems are further examined in terms of their complexity reduction effects. The research is supplemented with empirical evidence from several manufacturing companies.

Finally, the evaluation of the obtained results indicates a strong managerial and theoretical potential for the control and reduction of complexity in manufacturing industries and pinpoints areas for further investigation.

DANSK RESUMÉ

Man kan argumentere for at Kompleksitet nok er den største udfordring for produktionsvirksomheder Motivationen for yderligere at studere kompleksitet er en kombination mellem den eksisterende litteratur og de praktiske erfaringer fra industrien. Baseret på den nyeste tendenser forsøger virksomheder at levere et stigende produkter sortiment, med funktioner mere skræddersyede til at dække individuelle kunde behov, både ifm. product egenskaber og service. Denne nødvendighed fører til en betydelig forøgelse af kompleksiteten i virksomheden, som påvirker produktporteføljen, produktion og leveringskæden, markedssegmenter, it-systemer, og forretningsprocesser. For at identificere og eliminere kompleksitet, anvendes flere metoder, både af forskere og praktikere. Formål med af denne afhandling er at bidrage til den eksisterende viden om kompleksitet ledelsesteori *(Complexity Management)*.

Dette forskningsprojekt fokuserer på forholdet mellem produkt og proces kompleksitet. De mulige faktorer for at beskrive denne sammenhæng identificeres og defineres som kompleksitet omkostningsfaktorer (*Complexity Cost Factors* , CCFs). Ved at identificere disse CCFs, har dette forskningsprojekt til hensigt at analysere de mest relevante processer, hvor kompleksitet og omkostningerne er direkte relateret til produkt kompleksitet. På denne måde vil det være muligt at kvantificere de faktiske procesomkostninger relateret til hvert enkelt produkt variant. Desuden er initiativer vedrørende kompleksitet reduktion undersøgt. Standardisering i produktdesign, øget genanvendelighed af komponenter, udsættelse af kundeordre afkoblingspunktet (*customer order decoupling point,* CODP) og udnyttelse af konfiguration systemer er undersøgt med hensyn til deres bidrag til reduktion af kompleksitet. Forskningsprojektet er suppleret med empiriske data fra flere produktionsvirksomheder.

Afslutningsvis indikerer de opnåede resultater et stærk ledelsesmæssig og teoretisk potentiale for kontrol og reduktion af kompleksitet i for produktionsvirksomheder og fremhæver områder til yderligere undersøgelse.

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List of Abbreviations and Acronyms

ABC	Activity-based costing
ATO	Assembly-to-order
BOM	Bill of material
CCF	Complexity cost factor
CI	Complexity index
CM	Contribution margin
CODP	Customer order decoupling point
CR	Contribution ratio
CS	Case study
CTO	Configure-to-order
DC	Distribution center
DRM	Design research methodology
ERP	Enterprise resource planning
ETO	Engineer-to-order
HD	Heavy duty
LCCF	Lifecycle complexity factor
MTO	Make-to-order
NE	Numerical example
NR	Net revenue
PCS	Product configuration system
PLM	Product lifecycle management
PVM	Product variant master
RQ	Research question
S	Survey
SFU	Semi-finished unit
SKU	Stock keeping unit

1 INTRODUCTION

1.1 Background

Complexity exists everywhere; in nature, science and technology. This PhD project discusses the design of the research within the field of complexity management. Following the three steps approach (Booth et al., 2008) this research can be described in brief as following: "I am studying complexity in products and processes, because I want to find out the dependency between the management of complexity in industries and their profitability, in order to create a framework for companies to increase competitiveness". The motivation of further studying complexity is a combination between the existing literature and the practical experiences from the industry. Based on the latest trend companies are trying to supply a growing mix of more individualized product, both regarding products characteristics and support services. This tendancy leads to a considerable increase of the complexity in the company, which affects the product portfolio and all business processes. Yet this proliferation of the product portfolio is responsible for uneven cost distribution on the different variants, known as cost of complexity (Marti 2007, Schuh & Schwenk, 2001). In order to identify and eliminate complexity, several approaches are used, both by researchers and practitioners. The aim of this research is to contribute to the existing knowledge of complexity management theory.

1.2 Needs from academia

Since this research is within an inter-disciplinary field, the focus of this PhD project lays among the limits of several scientific areas (Figure 1-1). The main challenge is to overcome the differences in terminology, and ensure a valid interpretation of the of the term "complexity" within this interdisciplinary research field. Mass customization theory allows for analysis of the product portfolio and understanding the similarities and differences among the components and the final variants. Complexity theory describes the increasing complexity among the different business processes. Activity based costing theory provides methods for quantification of cost and profits of the products.

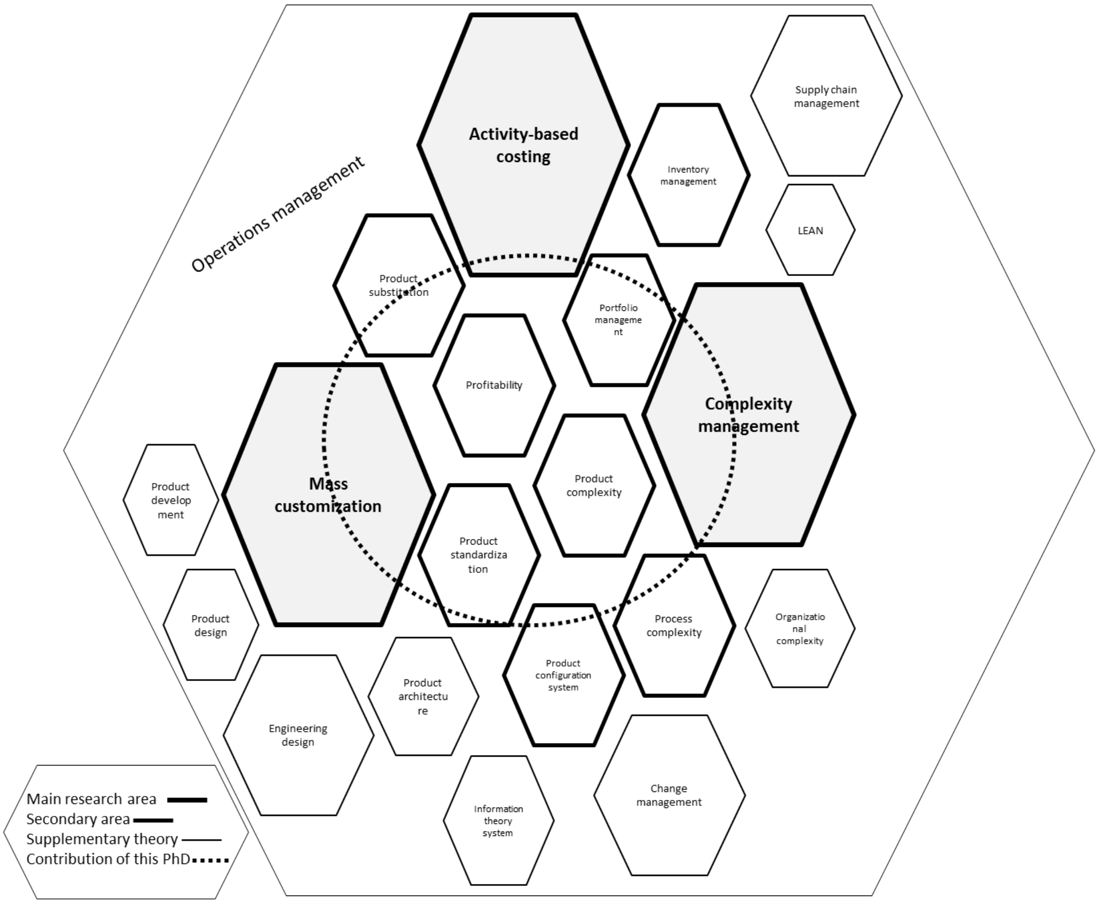


Figure 1-1 Scientific disciplines and contribution

Several approaches have been identified in the literature review for minimizing complexity in an organisation. Both academia and industry have contributed to this research field by either a structured approach, or by focusing on different aspects of complexity. This section discusses the limits of the existing methods for identification and quantification of complexity within the three main research areas of the conceptual framework: activity-based costing, mass customization and complexity management.

1.2.1 Activity-based costing

Numerous researchers (Kaplan 1994, Mariotti 2010, Zhang & Tseng 2007, Cooper 1998, Cooper & Kaplan 1998, Kaplan & Anderson 2007, Walker 1991) have developed methods for measuring product costing. Two of these methods have been more often used in the literature: Volume-Based Costing, Activity-Based Costing. Volume-Based Costing categorises all product related costs into material, direct labour and manufacturing overhead costs. This method is widely used, although it does not take into consideration the resources utilisation. Activity-based costing assigns the cost of the activity to each product (Drury, 1992). Activity-based costing is related to the assessment of the profitability of the product portfolio.

1.2.2 Mass Customization

This research area is examined in order to analyse and connect product variety with process variation, and based on this, to create an understanding of their relative importance for the cost (Blecker et al. 2006, Grussenmeyer & Blecker 2013, Pine 1993, Sanchez & Mahoney 1996). Mass customization enables manufacturers to provide a diversified product portfolio by combining the benefits of mass production and craft production (Duray 2002, Trentin et al. 2012). Yet, this increase in the offered product variety is also associated with a decrease in competitiveness and efficiency (Åhlström & Westbrook 1999, Blecker & Abdelkafi 2006, Kaiser 1995). To this end, complexity is examined in mixed-model assembly systems (Hu et al. 2011, Li et al. 2007), by using a multi-objective optimization approach to investigate the relation of product variety and manufacturing complexity.

1.2.3 Calculation of complexity costs

This area of study is of particular interest for this research, as the focus is to rationalize a product program in order to allocate the true complexity costs on the product variants (Hansen et al., 2012). Several research groups have been identified in this field discussing frameworks for assessing product profitability and cost behaviour (Zhang & Tseng 2007, Wilson & Perumal 2009, Danese & Romano 2004, Sivadasan et al. 2006, ElMaraghy et al. 2013, Mariotti 2010, Wan et al. 2012, Wang et al. 2011). This research deals with elimination of the "bad complexity", as defined by Wilson and Perumal (2009). The kind of complexity that is not required or value-adding in terms of components, processes, machineries etc., is the not-required variety, as defined by Ashby (1956).

1.3 Needs from industry

Complexity is a field of increasing interest, both for researchers and practitioners. Recent surveys conducted by IBM (2010) show that the main concern of 1,500 chief executive officers (CEOs) is the increasing complexity, which is considered to be the biggest threat for an organization. A survey performed by ATKearny (2009) in over 100 companies from more than 10 industrial sectors revealed that 84% of the companies consider complexity as a key cost factor, and that lack of transparency over complexity costs leads to inefficient management of complexity. The impact of product and portfolio complexity on operations and processes across the entire value chain is recognized by the managers, and is realized in different ways by each of them. For instance, plant managers face complexity caused by products in the form of increasing complexity in production planning and scheduling, supply chain managers realize complexity in the increasing inventories and finance managers in the growing level of investment in fixed assets (Brown et al. 2010). Ergo, complexity affects all business processes and it is being expressed in different ways. The causes for increasing complexity costs are specific for each company. In order to identify and quantify the most critical causes of complexity in a specific company, we need to identify the factors describing how product complexity leads to increased complexity and costs in a specific area of a company. Then tools for controlling and reducing of complexity are required, in order to enable a more efficient way of managing complexity within an organization.

1.4 Aim and scope of the research

The conceptual framework discussed before (section 1.2) is a starting point in order to identify how existing theories deal with complexity in products and processes. The critical literature review is not only used for deeper understanding of the so far developed approaches, but also it is part of the interpretative philosophical position in the chosen methodology (Meredith, 1989). In each research group identified so far, terminology is different. The interpretation of the used terms for complexity concepts is of great importance in order to allow future research equalise the diverse terms, embrace the existing knowledge, and use it in a constructive way.

Case studies are used to achieve reliability and validity in the results. Each study case is analysed in depth, following the research protocol to enable replication. In logical positivism, which is the paradigm that this research lays upon, “verification is how validity is ensured” (Karlsson, 2009).

The aim of this PhD project is to contribute to the theory and practise of complexity management. Based on the needs from both academia and industry, there is a need for a more efficient way to manage complexity in today’s highly competitive environment. Cost increases, sales losses and unsatisfied customers are problems faced by the industrial world. By addressing the issues of identification and reduction of complexity, a more adequate way of improving the current situation and overcome these challenges can be developed. To this end, complexity management is considered to be a promising paradigm for achieving the desired improvements.

1.5 Problem statement

In the last few years several surveys have been performed regarding complexity management. As discussed previously (section 1.3) the outcome of these surveys reveal that complexity is considered to be a threat, a key cost factor and the main reason for increasing complexity within an organization is the lack of transparency.

Nevertheless, complexity has both a positive and a negative meaning, which Wilson and Perumal (2009) define as “good” and “bad” complexity. “Good” complexity is considered as the increase in variety that is contributing positively in the product assortment and is value-adding for both the manufacturers and the customers. On the contrary, “bad” complexity is the type of variety that is not value-adding and it causes an increase in costs rather than increase in profitability. The impact of “bad” complexity is also realized in challenges in inventory management, imprecision on forecasted demand, undermining of sales and reduction of the operational performance (Wan et al. 2012, Alfaro & Corbett

2003, Fisher & Ittner 1999, Ton & Raman 2010). The optimal level of variety (Wan et al., 2012) is a relevant topic that has gathered attention in the last years.

Today's technological advances and production paradigms, i.e 3D printing technologies, industry 4.0, encourage individualization of products. That is the reason why the demand from customers for more specialized products that would satisfy their specific needs is increasing (MacDuffie et al. 1996, Dertouzos et al. 1989, Stalk & Hout 1990). The customers require products that would satisfy their each and every specific need and that would at the same time be within an accepted price range. This applies both to industrial and commercial sector (Bils & Klenow 2001, Fogliatto et al. 2012, Funke & Ruhwedel 2001).

The manufacturers based on these market requirements attempt to increase the variety in products and services that they provide to their customers (Wang, 2010). The reason for that is to sustain or even gain a competitive advantage in the market and manage to satisfy their customers (Wan et al. 2012, Bayus & Putsis 1999, Xia & Rajagoralan 2009). However, it should be mention that there is not always a direct relationship between an increase in offering variety through customization and an increased consumer value. The hidden challenge when it comes to managing this increasing variety in an effective and efficient way is difficult to be realized (Berman, 2002).

However, in order to support the production of a wider range of products and services for the customers the processes in the life cycle of the products are inevitably affected. The number and type of processes in production, distribution, sales and in general across the entire value chain are also increased. The automotive industry is a frequent discussed example (MacDuffie et al. 1996, Clark and Fujimoto 1991) in terms of increasing number of operations due to the increase of the product portfolio. Another example is firms that operate within a global supply chain. Then co-ordination is becoming challenging and less efficient, as the major teams are independent, even in terms of location (Rodriguez & Al-Ashaab, 2005).

With regards to efficiency, a decrease is expected in business processes, such as design, sales, distribution and production, as the focus is redirected to development of the product portfolio (Åhlström & Westbrook 1999, Blecker & Abdelkafi 2006). Moving from mass production to mass customization is accompanied with certain difficulties. To this end, it should be realized that there is a certain trade-off between the competitive advantage obtained from economies of scale, scope and learning, and the cost of customization (Pollard et al., 2008). Creating a value-adding variety both the customer and the producer, while facing increasing costs and lead time, are challenges that manufactures have to overcome (Haug et al., 2009). This trade-off is represented in the following figure (1-2) from ElMaraghy et al. (2013). The figure illustrates the challenge of increasing variety in low volume, highly individualized products in relation to profitability.

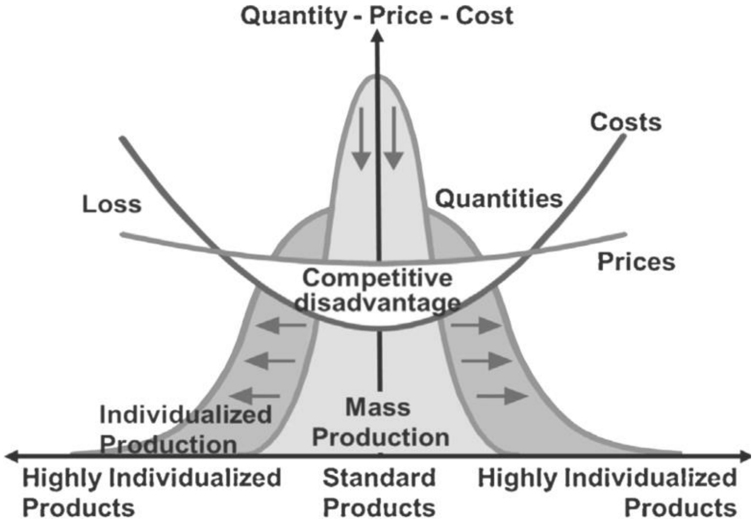


Figure 1-2 Product variety and cost distribution in individualized production (ElMaraghy et al. 2013)

The act of moving from mass produced to unique products, has a noticeable impact on the financial performance of the products, in terms of cost and profit, as it can be seen from figure 1-2. This impact from increased product variety is also realized in processes.

These sequential actions have as a result the increase of complexity both in products and processes. It is realized as a domino effect, starting by the customer needs, the need of companies to satisfy their customers' requirements and the increase in the number of processes in the value chain. This is also described as the cycle of the complexity trap, where companies are forced due to external factors to invest in new segments, causing more variety, higher complexity cost, higher prices or reduced profit, which overall results in a decrease in competitiveness (Kaiser, 1995).

Based on the above, the following figure (Figure 1-3) provides a graphical representation of the problem statement.

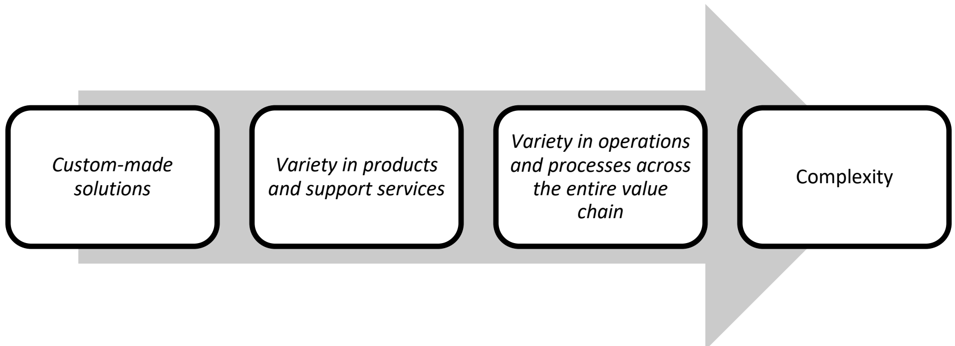


Figure 1-3 Chain of complexity increase

Summarizing, the problem under consideration is that manufacturing companies face the increasing complexity within the organisation. There is a need for developing methods to identify this complexity, and for having a structured approach to control and reduce it. The type of complexity that is not value-adding for an organisation is the focus of this research project. The management of complexity within an organization in order to improve its competiveness and profitability, at the same time without risking decreasing its product portfolio variety is also analysed in this research (Cunningham & Kwakkel, 2011).

1.6 Structure of the thesis

The thesis report is divided into 7 main sections. The first chapter gives a brief introduction to the current situation regarding management of complexity within an organization. The problem of increasing complexity is explained and the need for developing a structured approach to deal with it is discussed.

The second chapter presents the research design of the PhD project. The research method is selected and explained how it is applied to the different studies. Furthermore, the research questions (RQ) are formulated and explained, along with the case studies selected. Finally, there is an overview of the publications that are demonstrating how the research is communicated.

The third chapter consists of the literature related to complexity management. To begin with, there is an introduction to the different types of complexity that this research project is concerned with. Then methods for quantification of the complexity are discussed and initiatives to control and reduce complexity are presented. The main part of the literature research is the identification of complexity cost factors CCFs, which is presented in Papers A and G.

The fourth chapter provides an overview of the case studies. The selected case companies to provide empirical evidence for this research project are presented. Additionally, the research methodology and the set-up of the case studies are further discussed. In this chapter the developed frameworks are presented and their application on the case companies is discussed. The suggested methods discussed in this section are included in Papers B, C and H.

The fifth chapter presents the results of the 6 main studies conducted during this PhD project. The suggested methods for identification and reduction of complexity, which have been applied to 12 case studies in total, are discussed and evaluated. The results of the different studies performed during this PhD project are presented in this chapter and partially are included in the publications.

The last chapter of this PhD thesis is the overall conclusions of the research. Each RQ is answered, based on the results of the different studies. The contribution to the theory and the practice is discussed and, finally, pointers for further research are presented.

All the published work related to this PhD project is attached as appendix.

2 RESEARCH DESIGN

2.1 Research methodology

This chapter explains and discusses the research design of the Ph.D. project and introduces the main stages and concepts.

The Design Research Methodology (DRM) framework presented by Blessing and Chakrabarti (2009) is used as a research process framework for this PhD project. The main concept of the DRM framework is to view the research as it is constantly progressing through distinct research stages with specific objectives. The nature of this research methodology is heuristic, rather than algorithmic. The progress from one stage to another is not linear, yet it can be parallel with many iterations. Figure 2-1 provides a graphical representation of the DRM framework.

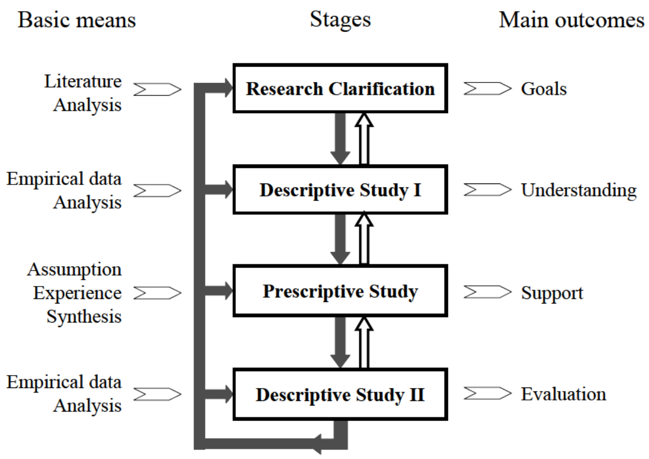


Figure 2-1 DRM framework (Blessing and Chakrabarti, 2009)

The DRM framework consists of four stages: Research Clarification, Descriptive Study I, Prescriptive Study, and Descriptive Study II.

The first stage, the Research Clarification (RC), examines the current situation and presents evidence to formulate a realistic goal for the optimal future situation. Furthermore, initial assumptions are made and evidence to support them is gathered. An initial literature research is also performed in the first stage.

The second stage, the Descriptive Study I (DS-I), provides further understanding to the examined phenomenon. The literature research is further performed to a higher level of detail and the goal of the study is elaborated, as the focus has become clear at this stage. In addition, the factors that influence the current situation are examined in this stage. Empirical data is gathered in that stage to better understand the current situation. At the DS-I the researcher has sufficient understanding of the existing situation and the factors that influence it, in order to proceed to the suggested improvements.

The third stage, the Prescriptive Study (PS), allows the researcher to correct and further elaborate on the initial problem description. At this stage the synthesis for improvement of the current situation takes place. Since at that stage there are sufficient data and experiences for the under investigation problem, scenarios can be developed. The scenarios for improvement address each of the factors identified that influence the current situation. However, at the PS stage it is not clear yet if the solution is effective, since it is based on the assumptions.

At the last stage of the DRM, the Descriptive Study II (DS-II), the validation of the research method takes place. Case studies are performed in order to verify the results. The outcome of the suggested scenarios is assessed. If the solution is not promising enough, the researcher returns to the DS-I stage to improve the factors and the assumptions, in order to re-evaluate the suggestions for improvement and consequently the results.

The DRM framework is selected in this research project as it consists of distinct stages; each of them sets specific goals and iteration among the different stages is possible. DRM enables the researcher to set clear goals and criteria for achieving and evaluating the success of the suggested solution. Moreover, the factors that influence the current situation towards the future desirable state are defined and the impact they have on the success is assessed. The DRM framework also allows the evaluation of the suggested approach and its application, as it enables an iterative research process. During the iterations, the findings are assessed and evaluated, so as to ensure the process of obtaining more valid results.

2.2 Research questions

The following section introduces the research questions (RQ). The RQ are initiated from the understanding of the challenges in the manufacturing world currently in relation to complexity management, as described in the problem statement (section 1.5). The final formulation and direction of the RQs is shaped after the extended review of the literature and the assessment of the gap in the existing literature.

The overall research objective addresses the focus of the research in regards to the management of complexity and it is formulated as follows:

Research objective:
Improve management of complexity in a manufacturing organization

In order to contribute to this relatively broad research objective and narrow down this research, this PhD project focuses on exploring the present theories for addressing complexity and elaborate on the need of establishing comprehensive methods to control and reduce complexity within a manufacturing environment. This results to the formulation of three main research questions. The first one (RQI) studies the roots of complexity and is concerned with the identification of the factors that are related to complexity costs.

RQ I. How can complexity in products and processes be identified?

1. *RQ1:* Which CCFs identified from the literature may be used to identify and quantify complexity costs in a manufacturing company?

Once the source of complexity is identified, the next step is to examine the effect between product and process complexity. Therefore, the second question (RQII) addresses the issue of complexity by its relation between products and processes.

RQ II. How to analyse the correlation between product and process complexity?

In order to provide answer to this research question the following propositions are formulated, to limit the focus of the research. The first proposition (P1) examines the relationship between product and process complexity, more specifically investigates how a change on the product affects the processes in terms of complexity. The second proposition (P2).

1. *Proposition 1 (P1):* Substitution on a module and component level contributes to improving of the production flow and capacity utilization of machinery and inventory.
2. *Proposition 2 (P2):* If it possible to reuse parts of the design of new projects from completed ones, then a significant reduction of costs of engineering, production and repairs after installation due to defects is achieved.

The next aspect to be taken into consideration is related to the reduction of complexity. When complexity is identified and controlled, the subsequent action is to reduce it and improve the performance of the product assortment. Thus the third question (RQ3) is developed in order to examine how to reduce complexity.

RQ III. How to reduce complexity in a manufacturing company?

This question is divided into three main parts (P3, RQ2, RQ3). P3 suggests a tool for a systematic approach of management of complexity. The operational approach under examination provides a method to guide the analysis of the future product assortment for complexity reduction.

1. *Proposition 3 (P3):* The four step operational method attempts to guide a systematic approach of product scoping, profitability analysis for CTO products, customers and competitor analysis and scenario creation for future product assortment.

The second part examines the performance of the supply chain in accordance to product complexity (RQ2). Production strategy, postponement and standardization are the aspects examined in relation to the profitability of the products.

2. *RQ2:* How can the operational and financial performance of a supply chain network for customized products be improved?
    a. *RQ2a:* How can customized products be categorized relative to their degree of customization?
    b. *RQ2b:* How can the potential for a postponement of the CODP and a standardization strategy be identified?
    c. *RQ2c:* How can postponement and standardization effects on costs and contributions margins be quantified?

The third part of the RQ III regarding complexity reduction addresses the use of a product configuration system (PCS) as a tool to reduce complexity and improve profitability of the product portfolio. The last question is formulated (RQ3) and it is tested in the three following propositions (P4, P5, P6).

3. *RQ3:* How a product configuration system can improve the profitability of the product assortment in a manufacturing organisation?

The remaining three propositions P4, P5 and P6 are focusing on complexity reduction.

a. *Proposition 4 (P4):* The accuracy of the cost calculations in the sales phase is increased by utilizing a PCS.

b. *Proposition 5 (P5):* Product profitability is increased by utilizing a PCS.

c. *Proposition 6 (P6):* Cost reduction is achieved through reducing complexity of a product's lifecycle processes by the use of a PCS.

    i. *Proposition 6a (P6a):* Application of PCS in the sales phase and increase of modular product range may lead to more standardized products and benefits proved in P1a indicate the scale of possible savings.

2.3 Research method

The research method selected for this PhD study is case-based. Several companies (12) have been chosen and used in order to test the suggested methodology. The companies are selected based on specific criteria that need to be fulfilled.

Case study is selected as the research method for this work, as it allows the research team to study the phenomenon in its natural settings (Benbasat et al., 1987). Additionally, case research is suitable for exploratory studies, as it allows deeper understanding of the relations among the variables and phenomena that are not fully examined or understood (Meredith, 1998).

In theory testing, case study research allows defining the set of variables, their relationships and predicted outcome (Wacker, 1998). In this research study the under examination construct is complexity. The predicted outcome is optimization of the process and product complexity. The degree of control of the research team during the process is relatively high when conducting case research, by having the flexibility and possibility to go back for additional data or clarifications required, while it is low regarding the outcome, when the researcher is obliged to keep distance and observe the results without affecting them (Sousa & Voss, 2009).

However the various benefits of applying case study research there are several challenges and limitations. The researcher must be unbiased during data collecting and analysis, as well as not to have an effect on the informants, in order to ensure internal validity (Sousa & Voss, 2009). Secondly, case research is time consuming and it requires skilled interviewers, in order to result in a rigorous research (Voss et al., 2002). Finally, in this research study, as it is based on several cases, generalizability of the conclusion is allowed. In order to ensure the external validity, the research protocol and research design are developed and discussed into detail for allowing further theoretical and literal replication of the study.

2.4 Challenges and delimitation

2.4.1 Data collection and limitations

Before starting data sampling from each company, the research protocol has to be defined. The design of the research protocol for the examined cases is used to ensure reliability and validity of the research (Yin, 1994). In addition, it is used as a guide tool for a well-structured research process and a clearly defined scope of data collection. The research protocol is used to obtain consistency within the several cases and guidance in terms of scoping data collection requirements and the relevant "key" informants. In order to create the research protocol, apart from the conceptual framework, the first case-study is also used as a pilot.

Data collection is achieved mainly from documentation (internal and external) and interviews with "key" informants. The following list of data has been identified as required from the first case study conducted, which is also considered as a pilot case-study for this research project:

- Bill-of-Materials (BOMs), in order to understand the decomposition of the finished product and be able to trace each and every component from sub-assembly to finished product.
- Component and finished goods inventories (amount, value).
- Sale price, cost value, sales number for each variant.
- Lead time, both from vendors to the case-company, and from the company to customers.
- Transportation and distribution network (inbound and outbound freight, handling costs).
- Net revenue and cost distribution.
- ABC analysis both of products and customers.

The primary source of acquiring this information is from the database of the organization (secondary data). Small companies might not have systems such as Product Lifecycle Management (PLM) or Enterprise Resource Planning (ERP), so data retrieval might be challenging. For instance, information for the lead time, if there is no internal database used, invoices and delivery documents are used for calculating lead times, as well as the percentage of on time delivery. Data are also acquired from related departments in a company. Designs of products are of great use, as they allow understanding functional units of the products, main components and how they are assembled.

As the research is based on retrospective cases, it is crucial to define a standard period, during which the data will refer to in all case-studies within this research. During to time limitation of the PhD project, the case-studies are examined for a period varying from 4 to 6 months. The data collected refer to one year period (12 months) for every case company.

Additional limitation during this research project is also considered the number of stakeholders involved in the PhD process. The PhD project is an applied research project, a combination of the academic and the industrial perspective on the topic of complexity management. The number and diversity of the stakeholders, including the divisions of Management Science and Engineering Design and Product Development from the Technical University of Denmark and the numerous companies used as case studies, has determined the scope of this research along the three years. The number of companies involved in this project in relation to the time limitation of the PhD project, made it difficult to apply the developed methods and tools more than once in each case. Yet, this limitation can be overcome by testing the suggested approaches to additional case studies in the future and also improve their applicability. To this end, the noteworthy number of case companies provided a significant opportunity for investigating and testing the developed methods in a variety of industrial sectors, to companies with different characteristics.

At last, the issue of bias from the researcher is also considered as a limitation to this research. Based on the literature and discussions with experts in this field (supervisors, researchers, representatives from the companies) the focus of this PhD study is determined. Therefore, there is considered to be unavoidable subjectivity. In order to overcome this limitation and increase an objective influence on the research focus, the research was presented in several conferences, seminars, workshops and journals. The reason for that is not only to communicate the results, but also to receive valuable feedback and engage other experts in a discussion regarding the topic of complexity management.

2.5 Research plan and verification

2.5.1 Research stages

The verification of the research is described by Pedersen et al. (2000), as the acceptance of the process of achieving them. For that reason, this research is structured based on the DRM framework. The research plan follows the DRM framework described in previous section (2.1).

To begin with, the first step is to identify the problem of complexity in manufacturing industries and provide evidence to make realistic assumptions. This is aligned to RC stage of the DRM. Part of the RC stage is included the first chapter of the thesis, as it contains the description of the existing needs from the academia and the industry, as well as the problem formulation. Then, the initial literature research is conducted in order to provide a first understanding of the current situation and enable the formulation of the RQ. This initial literature research covers the relevant theories regarding product and process complexity, quantification methods and concrete approaches of reducing complexity. The results of this research are presented in chapter three. Furthermore, a more in depth literature research is performed regarding the identification of the factors that are responsible for causing and increasing complexity both in products and processes, defined as CCFs. The related literature for managing complexity in products and processes is also examined in that stage. The results of these studies are included in Papers A and G.

The next step of the research plan is the DS-I stage, during which empirical data is collected for further understanding of the correlation between product and process complexity. Several aspects are taken into account regarding the investigation of that correlation. The effect of product substitution is examined and presented in Paper B and D. Moreover, the relationship between complexity and production strategy is analysed. This analysis is presented in Paper D. Another aspect that is related to product and process complexity is the utilization of a PCS, which is discussed in Papers E and F.

The PS stage of the DRM framework includes the phase of synthesis. During that phase the research focuses on examining each factor that has an influence on product and process complexity. Additionally, in the PS stage methods for improvement are developed; these methods address the factors identified from the literature. The two methods developed for this PhD research are presented in detail in chapter 4 (sections 4.3.1 and 4.3.2). The first method presents a framework for assessing and managing complexity between product mix and production flow. This framework is included in Paper H. The second method developed is an operational approach to be applied in assembly-to-order manufacturers for managing variety. This method is included in Paper C.

The last stage of the DRM framework enables the validation of the results. In the DS-II stage, the suggested methods are tested on case studies. In detail, the list of CCFs is tested in several case companies, as well as the suggested initiatives for management and reduction of complexity. These studies are presented in Papers A and G. Furthermore, the method developed in the previous stage for managing variety in products and processes is tested in case companies and the relevant results are presented in Paper H. Additionally, in this stage the relationship between postponement and profitability of products in global supply chains is tested in a case study and the outcome is assessed. This study is included in Paper D. Finally, the relationship between the utilization of a PCS and complexity is tested in two case studies. The first case examines the impact of utilizing a PCS on the complexity during the different lifecycle phases of a product. This study is presented in Paper J. The second case study tests the impact of the implementation of a PCS on the products' profitability; and the outcome is presented in Papers E and I.

The following figure illustrates the different research stages as described by the DRM framework in relation to the RQ and the appended papers (A-J). It should be mentioned that the various case studies conducted in parallel contribute partially to addressing each RQ sufficiently and to the verification of the research.

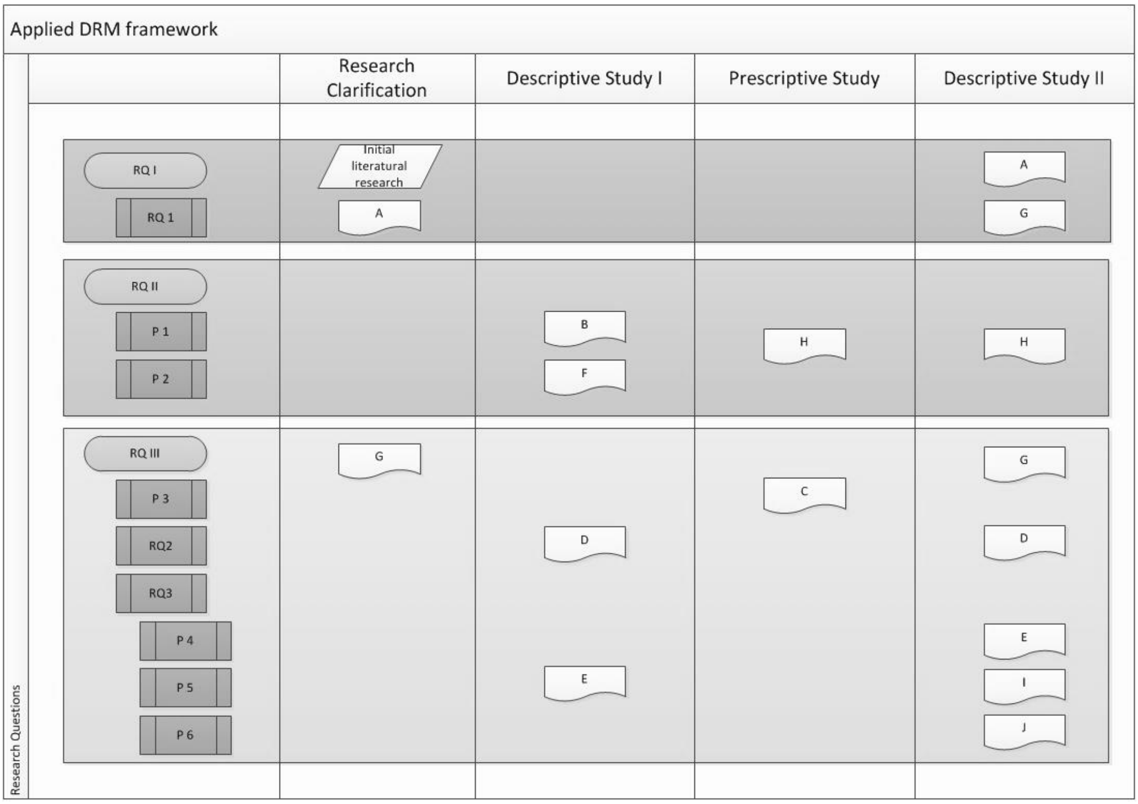


Figure 2-2 Applied DRM framework

2.5.2 Case studies

The methodology used in this work is case study research. Several companies have been investigated in order to test the relevant theory. During this PhD project access was provided to several case companies, which enabled for an investigation on a substantial number of companies across different industries. For that reason, the empirical foundation employed in this research project is based on 11 case studies and on one longitudinal case. In chapter 4, all the case companies are presented in detail.

A major part of the case studies was conducted within the manufacturing industry, which is of particular interest in the context of assembly-to-order (ATO), make-to-order (MTO) and engineer-to-order (ETO) production strategies. The vast majority of the case companies provide mechanical or electrical products. However, several case studies were performed outside of this market segment, such as commercial goods and building components, to achieve supplementary insight and triangulation of the developed results. The selected companies to be used as case studies fulfil specific criteria. All the companies are well established, operating globally and have a main production site in Denmark. Another important factor is that all companies have a strong interest in research and development, especially within the area of complexity management. On top of that, all companies are able to provide insightful primary and secondary data relevant for the analysis of complexity. Finally, all companies face challenges regarding complexity, in terms of decrease in sales or increase in costs, so as to make them suitable and fit within the boundaries of this research project.

As mentioned above, the required data for the analyses (i.e. profitability of product portfolios, product designs, BOMs) are sensitive and are usually a key competitive advantage for many manufacturing firms. Therefore, the case studies conducted throughout the research are presented in an anonymous way, to avoid any disclosure of critical information. The following table describes the case companies and their relation with the research questions and published articles.

Table 2-1 Case studies and their contribution

Case company	Research focus	Research sub-questions and propositions	Article
I	RQ I , RQ III	RQ1	A, G
II	RQ I , RQ III	RQ1	A, G
III	RQ I . RQ III	RQ1	A, G
IV	RQ I . RQ III	RQ1	A, G
V	RQ I , RQ III	RQ1	A, G
VI	RQ I , RQ III	RQ1	A, G
VII	RQ I , RQ III	RQ1	A, G
VIII	RQ II	P1	B, H
IX	RQ III	P3	C
X	RQ III	RQ2	D
XI	RQ III	RQ3 - P4, P5	E, I
XII	RQ II – RQ III	RQ2 - P2, P6	F, J

2.5.3 Communication of the research

The following articles provide the main contribution to this research project. All the articles are submitted to academic journals and conferences within the field of complexity management. The articles are appended in the end of this dissertation.

The appended Papers G, H, I, and J use the same case studies as the Papers A, B, E and F respectively. However they include a more thorough description of the contributions of the related studies and show the several iterations that took place during this PhD research.

A. Identification of complexity cost factors in manufacturing companies. / Myrodia, Anna; Hvam, Lars. Proceedings of the 22nd EurOMA Conference: Operations Management for Sustainable Competitiveness. European Operations Management Association, 2015.

B. Two-way substitution effects on inventory in configure-to-order production systems. / Myrodia, Anna; Bonev, Martin; Hvam, Lars. Proceedings of the 2015

IEEE International Conference on Industrial Engineering and Engineering Management (IEEM). IEEE, 2015. p. 48-52.

C. Managing Variety in Configure-to-Order Products – Development and application of an operational method. / Myrodia, Anna; Hvam, Lars. In: International Journal of Industrial Engineering and Management, Vol. 5, No. 4, 2014, p. 195-206.

D. Reconfiguring variety, profitability and postponement for product customization with global supply chains. / Bonev, Martin; Myrodia, Anna; Hvam, Lars. Managing Complexity. Proceedings of the 8th World Conference on Mass Customization, Personalization, and Co-Creation (MCPC 2015). ed. / J. Bellemare; S. Carrier; K. Nielsen; F.T. Piller. Springer, 2016. (Springer Proceedings in Business and Economics).

E. Impact on cost accuracy and profitability from implementing product configuration system – A case-study. / Myrodia, Anna; Kristjansdottir, Katrin; Hvam, Lars. Proceedings of the 17th International Configuration Workshop. ed. / Juha Tiihonen; Andreas Falkner; Tomas Axling. University of Helsinki, 2015. p. 11-17 (CEUR Workshop Proceedings).

F. Impact of the utilization of a product configuration system on product's life cycle complexity. / Myrodia, Anna; Kristjansdottir, Katrin; Shafiee, Sara; Hvam, Lars. Proceedings of the 5th World Conference on P&OM. Joining P&OM forces worldwide: Present and future of Operations Management, 2016.

G. Complexity management in manufacturing companies. / Myrodia, Anna; Hvam, Lars. 2016. (Submitted journal article)

H. Managing complexity of product mix and production flow. / Myrodia, Anna; Bonev, Martin; Hvam, Lars. 2016. (Submitted journal article)

I. Impact of product configuration systems on product profitability and costing accuracy. / Myrodia, Anna; Kristjansdottir, Katrin; Hvam, Lars. 2016. (Submitted journal article – Accepted with minor changes)

J. Product configuration system and its impact on product's life cycle complexity. / Myrodia, Anna; Kristjansdottir, Katrin; Shafiee, Sara; Hvam, Lars. Accepted article in Proceedings of the 2016 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM). IEEE, 2016

3 THEORETICAL BASIS

This chapter establishes the main ground of the theoretical background of this research. This is an interdisciplinary study, as explained in section 1.2 and it touches upon several research areas. The following figure illustrates the different disciplines that are the main focus areas in operations management and create the conceptual framework of this PhD project.

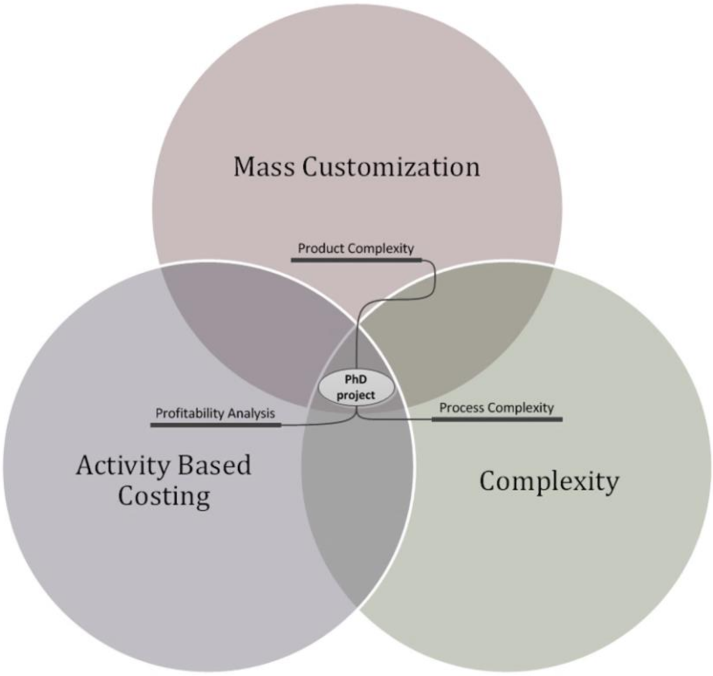


Figure 3-1 Conceptual framework

After introducing the RQs and defining the conceptual framework, an extended literature review is conducted within the intersection of these three focus areas. The main keywords for searching are "complexity cost factors", "product complexity", "process complexity" and “complexity drivers”. The reason for introducing the term “driver” is the fact that early in the review process, it has been noted that many articles use this term within the same meaning as others use the term “factor”, such as Perona and Miragliotta (2004) and Schaffer and Schleich (2008). However, both words when used in the articles reviewed refer to facts that cause, stimulate and increase complexity.

This chapter is also concerned with understanding and analyzing the complexity in processes. The relationship between product and process complexity is also investigated and introduces the concept of CCFs. Different quantification methods are discussed regarding the analysis of profitability of the product assortment and the calculation of complexity. The last part of this chapter elaborates on the concepts and methods that can be used for reduction of complexity.

3.1 Complexity management

This section elaborates on the various aspects that are related to the concept of complexity management. Product complexity is discussed in terms of product design principles and profitability theories. In a similar way the complexity in the lifecycle processes of a product are investigated, as well as the correlation between product and process complexity. Finally, the factors that have been identified causing complexity costs are grouped under the relevant processes of the industrial process classification framework (APQC).

3.1.1 Product complexity

3.1.1.1 Product complexity and architecture

The concept of complexity has been studied from various perspectives. In engineering domains, term is generally related to the design of product architectures and the commercial variety created through them (Martin & Ishii, 2002). With product architectures, engineers create an abstract representation of a product design. They express how product functionality is realized by a set of interacting physical components and their formally expressed interfaces (Ulrich, 1995). By rearranging the structural characteristics and adding optional components to the architecture, the design of the product and its variety can be altered. In industries with higher needs for customization, this rearrangement can play an essential role the economical success of a product (Pil & Holweg, 2004). Since high product-mixes tend to require an increase number of components and interchangeable options, the design and handling of such products can be a challenge (Veldman & Alblas, 2012). Measures defining the resulting complexity are diverse and typically emphasize either the product design or its handling. Product oriented complexity measures focus on the structural characteristics of the product architecture, i.e. number of components and the nature of their relationships (Sosa et al., 2007). A way to limit the resulting complexity is to increase the amount of common components across variants in a reusable platform and by introducing interchangeable modular options (Erens & Verhulst, 1997). Product platforms are also taken into consideration when it comes to analysis of product complexity, as they consist of components and interfaces that establish a common structure in order to design and produce new product families (Meyer & Lehnerd, 1997)

With reference to business and marketing concepts, complexity is associate to variety (Byrne, 2007), where the reason for variety may be related to the number of parts and their related features (Patzak, 1982). Ways to reduce such variety induced complexity essentially deal with reducing the stock keeping units (SKUs) in an organization. The decision making regarding the need for any SKU is based on the Pareto or ABC principle (Brynjolfsson et al., 2011).

However, the focus of this research is on eliminating not value adding complexity. Complexity is often related to variety and profitability. Profitability varies greatly among products and product families and that could be an indication of which products are positively contributing to a company's performance. As a result, the analysis of products profitability is required. In order to determine this, the ABC product classification method is used.

3.1.1.2 Product profitability analysis

The ABC analysis was initially introduced by Pareto (Pareto, 1971) and has been further used in operations management domains. It categorizes products into A, B, and C based on the relative distribution of cost or the usage of the SKUs.

With the rapidly increasing number of variants in the recent years, manufacturers are trying to maximize the variants offering, in order to serves their customers' needs, increase competiveness and identify the market niche. This variety induced complexity is also challenging for achieving the right cost distribution by allocating the overhead cost to the variants (Blecker et al., 2006). In other cases, additional factors rather than profit and costs are of great importance. For instance, time, quality and flexibility are dimensions for analysis of performance by using the activity-based costing approach (Kloock & Schiller, 1997).

However, not all variants contribute to the net revenue neither at the same percentage. As a result large product variety does not imply for stable long-term profitability (Koo et al. 2009, Liiv 2006, Sarkis 1997). Moreover, an increase in turnover due to product proliferation does not necessarily result in an increase in profit, and this link between revenue and profits can be associated to the level of economies of scale (Lancaster, 1990). For that reason the ABC product differentiation becomes imperative. The ABC product prioritization can include a number of additional aspects, which have been of great importance for inventory management within operations management domain, such as lead time, substitutability and variability (Benito & Whybark, 1986). Recent studies have shown relations between the ABC product differentiation and the lot size (Yücel et al., 2009) or substitution (Hsu et al., 2005).

Hansen et al. (2012) perform an ABC analysis of product profitability by calculating the contribution margin (CM)and net revenue (NR) of each variant, and then making the ABC classification by using the Pareto Law (Pareto, 1971).

A hypothetical example of an ABC product categorization is illustrated in the following figure. The products are categorized into A, B and C groups based on their contribution margin and net revenue. For the calculation of the contribution margin, the direct costs are subtracted from the net revenue, resulting in revealing the profitability of the products. The ABC grouping is based on the Pareto principle (Pareto, 1971). As it can be seen from the figure below, 80% of the products are categorized as C, 15% as B and 5% as A. The A products are the most profitable ones, that are making the actual contribution to the overall profitability.

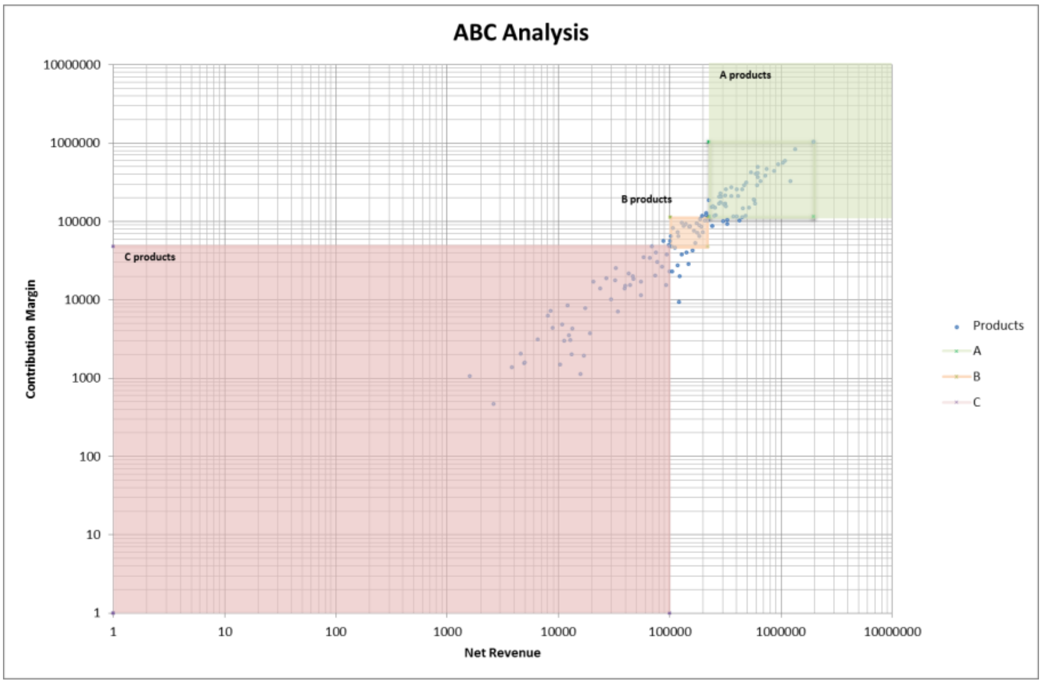


Figure 3-2Hypothetical example of an ABC product categorization.

To a broader extent, Wearden (1981) lists the main factors that have to be included in a performance analysis. Turnover, profit and ratios, sales records, capital utilization and overheads are among them.

Flapper et al. (2010) discuss two strategies regarding product assortment. The first investigates the contribution of each product to the total net profit, while the second strategy has the same approach but for customers. Two mathematical models are developed for determining the optimal product and customer based assortment.

A similar approach is also discussed by Wheeldon (1986); Wheeldon suggests that short-term solutions should be oriented towards existing customers when defining a new product range. A framework for evaluation of a product line design is introduced by Li and Azarm (2002). The framework includes factors that affect the evaluation, such as commonality of variants, customer preferences, competitors and business goals. In other words, the framework suggests an internal and external analysis of a company.

In addition, different methods have also been used by several researchers regarding product profitability, such as mathematical modeling and heuristics. Dobson and Kalish

(1993) create a mathematical program to quantify the profit of a company, taking into account product desirability and fixed and variable costs. Additionally, the suggested operational method can also include, apart from a company's own products, similar competitive products. A more customer-oriented ABC analysis is introduced by Juran (1995) based on the Pareto Law, and is discussed by Liiv (Liiv 2006, Liiv 2007), using demand association in order to improve product classification.

These publications have been looking merely into the profitability analysis of products in terms of identifying factors and methods. The rest of the literature review discusses the existing research on portfolio management. However, it also highlights the interconnection between these two areas.

3.1.1.3 Portfolio management

By performing a critical literature review, it is realized that portfolio management is highly related to profitability analysis.

Starting from a more general approach, is to point out the need of diversity inputs when developing a product strategy. Muneer and Sharma (2008) conclude that production planning, product development, and sales are these aspects. Wheeldon (1986) discusses the different aspects that have to be taken into consideration when identifying a product policy. He makes an initial step in connecting the market-oriented factors that influence the profitability of the products and factors that should be considered in developing a product strategy. The local market where a company operates, the international markets of current or future operation and the technological status of both a company's own products and of those offered by competitors are subjected to further analysis. This will provide the company with a valid perspective regarding its position in the market

The identification of the optimal set of products for a company so as to maximize its value, is also discussed by Gonzalez et al. (2001). Value is realized as the sum of benefits of a set of products minus all costs created throughout product lifecycle activities. This definition of value, and more specifically of the benefits and costs, differs slightly from the economic values used in the ABC classification suggested by Hansen et al. (2012).

From a different perspective, De Reyck et al. (2005) assess the relation between portfolio management and information technology projects, and identify portfolio performance as one of the objectives. The suggested operational method for financial analysis includes the calculation of return on investment (ROI), internal rate of return (IRR), net present value (NPV) and economical value added (EVA). Similar approaches have been suggested by Benaroch (2002) and McGrath and Macmillan (2000). Financial analysis could also be seen as a part of profitability analysis.

A framework for examining the decisions regarding a company's product variety is presented by Ramdas (2009). The number of products, the targeting markets, and the time for each product to be introduced are identified as the key drivers of variety creation. Its implementation is related to a company's resources and capabilities.

3.1.2 Process complexity

Complexity is realized both in products and processes of the entire life cycle. Five areas of complexity are identified by Foster and Gupta (1990): product design, procurement, manufacturing process, product range, and distribution. Rathnow (1993) distinguishes complexity cost between those that occur only once, at the introduction of the new variant, and those that re-occur during the entire lifecycle of the product. Rommel et al. (1993) identifies and calculates the complexity costs for the business processes, by using a case study in the automobile manufacturing. The research concludes with the cost structure and the break-down of complexity costs to different processes. 15-20% of the total costs are considered as complexity costs, which are allocated to several business processes, such as inventory, production, logistics and sales.

Alternatively, complexity can be studied from the perspective of organizations and the way they deal with complexity. Samy and ElMaraghy (2012a) for example define complexity as degree to which product variety can complicate the production process. In the same concept, Arteta and Giachetti (2004) point out that complexity is preventing a company from changing its organizational structure, processes and products, and is connected to the interrelationships of the system elements. MacDuffie et al. (1996) quantify product complexity to test the impact of product variety on quality and productivity in a LEAN manufacturing environment. Several researchers have performed similar work (Fisher & Ittner 1999, Fujimoto et al. 2003, Martin & Ishii 1996) where the focus has been to measure how the production process is affected by product complexity, related to the increasing number of variations. An approach widely used for measuring organizational complexity seen as a system consisting of the interplay between products and processes is based on entropy measure (Arteta & Giachetti, 2004). According to the authors, system complexity arises not only from components and their interrelations in a structure, but also from the emergent change of these relations, caused by different states of available material and information flow. To cope with the dynamical element of complexity, these different states are assigned probability measures.

Lot size and demand are also factors related to product and process complexity. To this end, Masuchun and Masuchun (2008) have created a model to determine the optimum lot size in order to match the production flow and the customers' demand. Bottleneck machines affect the production rate, and in order to maximize efficiency the lot size should be large (Koo et al., 2009). Furthermore, Yu (2012) examines the production lot size in relation to the demand. In this way, the production can benefit from the economies of scale by producing in high volumes. Yet, this has as a consequence a certain restriction to the variety (Jacobs & Swink, 2011). Benjaafar and Gupta (1998) are suggesting that the number of final products and the lot size are commensurate, however these results are based on the assumption that the production facility is able to expand or change.

3.1.3 Link between product and process complexity

3.1.3.1 CCFs

Several authors have performed literature review studies in the research field of complexity. Bozarth et al. (2009) discuss the main factors responsible for complexity in the whole supply chain, from manufacturing schedule to globalization of the supply chain. Marti (2007) presents the existing concepts in managing product complexity and assesses them with five criteria, such as product strategy, market aspects, product architecture, quantification methods and applicability in practice.

Complexity is three-dimensional, as it rises in products, processes and organizational structure, and there is an interconnection and a strong impact among these three types of complexity (Wilson and Perumal, 2009). In a similar way, Simon (1962) defines a *complex system* as one system that consists of many elements, and these elements interact in a non-simple way. Yet, for the aim of this research approaches analysing complexity in organizational structures (Child et al., 1991) or in corporate networks (Azadegan & Dooley, 2011) are not investigated as they fall out of scope.

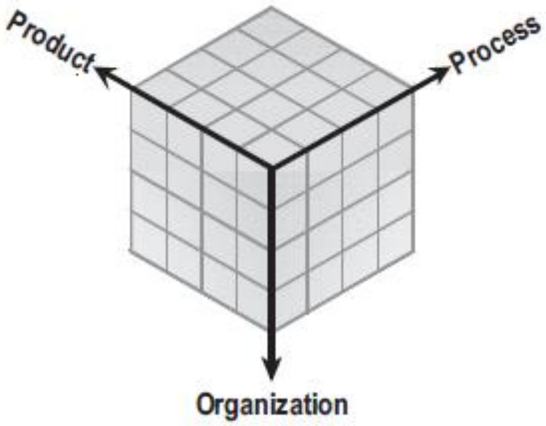


Figure 3-3 Complexity Cube (Wilson and Perumal, 2009)

Forza and Salvador (2002b) examine the benefits of implementing a product configuration system in an ATO manufacturer. In order to assess these benefits, the ordering and production processes have to be examined. This resulted in identifying the number of finished goods as the main source of complexity in both the information flow from the sales personnel to production and shop floor activities. The complexity in the production and assembly processes, identified in supply, production scheduling and manual assembly operations, is highly related to both number of components and number of finished goods (Hu et al., 2011). Huatuco et al. (2010) discuss entropy-related complexity both in the production floor, and in the supplier and customer interfaces.

One cause of increasing complexity in manufacturing environments is the product variety (Schaffer & Schleich 2008). The effect of product variety is related to inventory and production costs. In tandem with these results, Wildemann (2001) performs an empirical study in manufacturing industries, regarding how the number of product variants affects the unit costs. Two types of industries are examined, with traditional and segmented and flexible automated plants. The results have shown that with the double number of product variants in the production program, the unit costs would increase about 20-35% for industries with traditional manufacturing systems. At the same time, in segmented and flexible automated plants, the unit costs would increase about 10-15%. Yet, research has indicated that unsatisfied needs due to missing or wrong variety can also be contributing indirectly to an increase in complexity cost (Rathnow, 1993). For that reason the complexity costs can be reduced or even avoided if the product variety is scoped to the optimum range (Lechner et al., 2011)

Nevertheless, complexity is one the reasons that not every variant contributes positively to the net revenue of the company. The profitability of each product variant is, in addition, related to the production flow in terms of lot size and SKUs (Yücel et al., 2009). ElMaraghy and Urbanic (2003) introduce two factors of increasing complexity, firstly the number and diversity of features to be manufactured, assembled and tested, and secondly, the number, type and effort of the tasks required to produce the features. Samy and ElMaraghy (2012b) define complexity as "a measure of how product variety can complicate the production process". Except for the variety perspective, complexity of a systems is also related to connectivity and variability of its elements, for instance how connected the elements of a system are and how strong their number and connectivity differs (Patzak 1982, Ulrich & Probst 1988).

The cost of introducing a new variant happens once, while other cost areas, i.e. maintenance are re-occurring (Rathnow, 1993). Yet, costs immediately related to the introduction and maintenance of variants may be considered as direct complexity cost. This variant may require additional handling or treatment, such as quality management, different tooling, more inventory or new material. Labour and material costs can be directly assigned to each particular variant, while other cost categories have to be allocated proportionally as overhead cost (Anderson, 1995).

Blecker et al. (2004) suggest mass customization as a strategy for eliminating complexity caused by increasing variation in product architecture, inventory and order taking process. Additionally, they discuss the relations between mass customization and complexity. Mass customization principles are investigated from two different perspectives. On the one hand, when applied as a pure customization strategy, they increase the product variety, which results in high planning and scheduling complexity. On the other hand, as customer ordering decoupling point moves towards the front-end, then mass customization reduces product configuration and inventory complexity (Blecker et al. 2004).

The causes for increasing complexity costs are specific for each company. In order to identify and quantify the most critical causes of complexity in a specific company, we need to identify the factors describing how product complexity leads to increased complexity and costs in a specific area of a company. For this we introduce the concept of a CCF.

We define a CCF as a factor that causes uneven distribution of the costs among the different products. For example, the set up and change over times of the machines in production vary among the different products, as well as the batch size in a way that high volume products would have relative low set up cost per item, while low volume products would have relative high costs per item. By assigning the actual set up time for each and every product, differences are noted to what was considered to be fixed cost, and was so far distributed equally among all the products. In order to calculate and reduce complexity costs, but also to reveal the real contribution of each product to the profit, the need of calculating the complexity cost becomes imperative. A CCF is a factor that describes how product portfolio complexity (e.g. number of finished goods) has an impact on the costs of a specific process step. Examples of CCFs are setup times in production, scrap of materials in setup of machines, sales order handling, inventories of finished goods, and freight of finished goods to warehouses.

By identifying the CCFs we intend to analyze the most relevant processes where the complexity and cost are directly related to the complexity of products. In this way, it will be possible to quantify the exact cost impact on those processes for each product variant (e.g. one specific product would have a cost of set up cost per product at 3 euro per product, while another product would have a setup cost at 30 euro per product due to relative smaller batch sizes). By this we can allocate the specific costs of complexity to each product thus making a more exact quantification of the costs of complexity per product. This makes it possible for the company to evaluate the product range and eventually eliminate low volume products with relative high complexity costs. The approach differs from activity-based costing in that we strive to identify the most significant CCFs and only allocate these costs elements to the products. Furthermore we focus in particular on the correlation between complexity in the product assortment and the cost of processes.

3.1.3.2 APQC process classification standard

The next step of the literature review focuses on identifying a framework for classification of processes. The reason for using such a framework is to obtain an overview of the processes in a manufacturing company, enable comparison among the organizations and categorize the CCFs under the relevant processes. The industrial standard APQC provides such a process classification (APQC, 2015). The APQC standard is selected as a classification framework because it describes all the processes in every industrial environment; as a result, it can be applied to any manufacturing company. The APQC process classification framework creates a common ground for organizations that operate in different production and market areas, and it is claimed to be “the most used process framework in the world” (APQC, 2015).

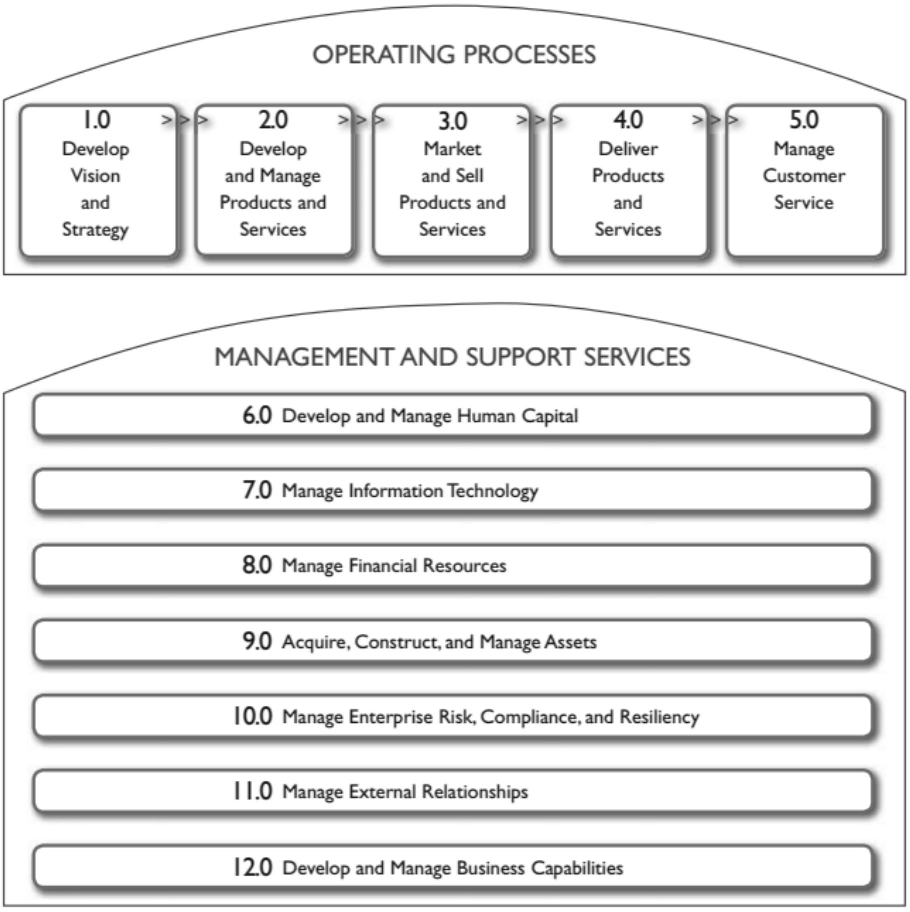


Figure 3-4 APQC Industrial Framework (APQC, 2015)

3.1.3.3 Categorization of CCFs under the industrial process standard

The following tables (3-1 to 3-5) provide an overview of the results from the literature review. Each table refers to one of the process groups, as they are described in the APQC process classification framework. Each table describes the CCFs related to a process group, as described in the APQC standard. Under each CCF, the authors working with it are listed. When the names are in bold, it means that the article discusses quantification methods. When parentheses follow the name of the authors, they indicate that there is empirical evidence, such as case-study (CS), survey (S) or numerical example (NE). Articles are listed into two groups with reference to discussing the CCFs related to the number of components and/or the number of finished goods, taking into account both their quantity and diversity/variety.

Table 3-1 Articles discussing "Plan for and align supply chain resources"

	No of components
No of material handling systems	**Kuzgunkaya & ElMaraghy 2006** (CS), **Samy & ElMaraghy 2012a** (CS), **Garbie & Shikdar 2011a** (NE), **ElMaraghy et al. 2012** (CS)
State of material handling systems	**Kuzgunkaya & ElMaraghy 2006** (CS), **Samy & ElMaraghy 2012a** (CS)
Type of material handling systems	**Kuzgunkaya & ElMaraghy 2006** (CS), **Garbie & Shikdar, 2011a** (NE), **Samy & ElMaraghy 2012b** (CS), **Zhang & Tseng 2007** (CS)
Material flow pattern	**ElMaraghy et al. 2014** (CS), **Samy & ElMaraghy 2012a** (CS), **Thyssen et al. 2006** (CS), **Garbie & Shikdar 2011a** (NE), Hayes & Clark 1985 , Urbanic & ElMaraghy 2006 (CS), Khurana 1999, Isik 2009

In the table above (3-1), all the identified CCFs from the literature are listed. These factors refer to the activities of supplying and planning of the resources, as a result they are relevant only for the number of components but not applicable for the number of finished goods. In this context of a manufacturing industrial environment raw material are considered as resources. That is the reason why the CCFs refer to the material handling systems and flow. All four CCFs identified in the literature are supported by empirical evidence, mainly case-studies and numerical examples.

Table 3-2 Articles discussing "Procure materials"

	No of components
No of suppliers	**ElMaraghy et al. 2012, Hu et al. 2008, Perona & Miragliotta 2004** (CS), **Jacobs 2013,** Isik 2009, **Bozarth et al. 2009** (S)
Location of suppliers	**Hu et al. 2008**
Cost of sourced components	**Foster & Gupta 1990** (CS)

The second table (3-2) presents the factors related to procurement. Suppliers, regarding their number and location, are identified as CCFs related to the number of components. As it is mentioned above, the CCFs are relevant only for the number of components but not applicable for the number of finished goods. For example, by having fewer suppliers the company could achieve lower prices for the materials bought, as they are getting higher volumes. In that sense, the number of suppliers causes uneven costs to the products. Quantification examples are also provided in the literature for the CCFs identified above, in addition to empirical evidence.

Table 3-3 Articles discussing "Produce/Manufacture/Deliver product"

	No of components
Capacity utilization	**ElMaraghy et al. 2012, Garbie & Shikdar 2011a** (NE), Blecker & Abdelkafi 2006, Isik 2009
Assembly	**ElMaraghy et al. 2012, Hu et al. 2008, ElMaraghy et al. 2014** (CS)**, Samy & ElMaraghy 2012a** (CS)**, Thyssen et al. 2006** (CS), Blecker & Abdelkafi 2006**, Samy & ElMaraghy 2012b** (CS)**, Khurana 1999,** Isik 2009
Tools	**Hu et al. 2008, Samy & ElMaraghy 2012a** (CS)**, Deshmukh et al. 1998** (NE), Urbanic & ElMaraghy 2006, **Zhang & Tseng 2007** (CS)
Operator	**Hu et al. 2008,** Urbanic & ElMaraghy 2006 (CS)**,** Gershwin 1994, **Zhang & Tseng 2007** (CS)
No of machines	**Kuzgunkaya & ElMaraghy 2006** (CS)**, ElMaraghyet al. 2014** (CS)**, Samy & ElMaraghy 2012a** (CS)**, Garbie & Shikdar 2011a** (NE)**, Deshmukh et al. 1998** (NE), **Perona & Miragliotta 2004** (CS)**, Samy & ElMaraghy 2012b** (CS)**,** Urbanic & ElMaraghy 2006 (CS), Isik, 2009, **Zhang & Tseng 2007** (CS)
Type of machines	**Kuzgunkaya & ElMaraghy 2006** (CS)**, Garbie & Shikdar 2011a** (NE)**, Samy & ElMaraghy 2012b** (CS)**,** Urbanic & ElMaraghy 2006 (CS)
State of machines	**Kuzgunkaya & ElMaraghy 2006** (CS)**, Samy & ElMaraghy 2012b** (CS)
No of buffers	**Kuzgunkaya & ElMaraghy 2006** (CS)**, Samy & ElMaraghy 2012b** (CS)**, Samy & ElMaraghy 2012a** (CS)**, Khurana 1999**
Type of buffers	**Kuzgunkaya & ElMaraghy 2006** (CS)**, Samy & ElMaraghy 2012b** (CS)
State of buffers	**Kuzgunkaya & ElMaraghy 2006** (CS)**, Samy & ElMaraghy 2012b** (CS)

Failure	**Kuzgunkaya & ElMaraghy 2006** (CS)**, Samy & ElMaraghy 2012a** (CS)**,** Hayes & Clark 1985, **Urbanic & ElMaraghy 2006** (CS)**,** Gershwin 1994, **Zhang & Tseng 2007** (CS)
Set up	**Thyssen et al. 2006** (CS)**, Garbie & Shikdar 2011a** (NE), **Deshmukh et al. 1998** (NE), **Benjaafar et al. 2004,** Hayes & Clark 1985**,** Urbanic & ElMaraghy 2006 (CS)**,** Gershwin 1994, **Zhang & Tseng 2007** (CS)
Change-over	**Thyssen et al. 2006** (CS)**, Garbie & Shikdar 2011a** (NE), **Deshmukh et al. 1998** (NE), **Benjaafar et al. 2004,** Hayes & Clark 1985**,** Urbanic & ElMaraghy 2006 (CS)**,** Gershwin 1994
Waiting times	**Thyssen et al. 2006** (CS)**, Garbie & Shikdar 2011a** (NE), **Deshmukh et al. 1998** (NE), Hayes & Clark 1985**,** Urbanic & ElMaraghy 2006 (CS)**,** Gershwin 1994
Batch size	**Thyssen et al. 2006** (CS)**, Garbie & Shikdar 2011a** (NE), **Deshmukh et al.1998** (NE), **Benjaafar et al. 2004, Zhang & Tseng 2007** (CS)
Capital costs (rent/heating)	**Thyssen et al. 2006** (CS)**, Perona & Miragliotta 2004** (CS)
Production lines	**ElMaraghy et al. 2012, Kuzgunkaya & ElMaraghy 2006** (CS)**, Hu et al. 2008, Garbie & Shikdar 2011a** (NE), Blecker & Abdelkafi 2006**, Deshmukh et al. 1998** (NE), **Jacobs 2013**
Job shop	**Deshmukh et al. 1998** (NE), **Khurana 1999, Zhang & Tseng 2007** (CS)
	<u>No of finished goods</u>
Capacity utilization	**ElMaraghy et al. 2012, Hu et al. 2008, Garbie & Shikdar 2011a** (NE), Blecker & Abdelkafi 2006, Isik, 2009
Assembly	**ElMaraghy et al. 2012, Hu et al. 2008, Samy & ElMaraghy 2012b** (CS)**,** Blecker & Abdelkafi 2006**, Samy & ElMaraghy 2012a** (CS)**, Schaffer & Schleich 2008** (CS), Isik 2009
Tools	**Hu et al. 2008, Samy & ElMaraghy 2012a** (CS)**, Garbie & Shikdar 2011a**

	(NE), **Deshmukh et al. 1998** (NE), **Zhang & Tseng 2007** (CS)
Operator	**Hu et al. 2008, Zhang & Tseng 2007** (CS)
No of machines	**Kuzgunkaya & ElMaraghy 2006** (CS), **ElMaraghy et al. 2014** (CS), **Samy & ElMaraghy 2012b** (CS), Sivadasan et al. 2002 (S), **Garbie & Shikdar 2011a** (NE), **Deshmukh et al. 1998** (NE), **Samy & ElMaraghy 2012a** (CS), Isik 2009, **Zhang & Tseng 2007** (CS)
Type of machines	**Kuzgunkaya & ElMaraghy 2006** (CS), **Garbie & Shikdar 2011a** (NE), **Samy & ElMaraghy 2012b** (CS)
State of machines	**Kuzgunkaya & ElMaraghy 2006** (CS), **Samy & ElMaraghy 2012b** (CS)
No of buffers	**Kuzgunkaya & ElMaraghy 2006** (CS), **Samy & ElMaraghy 2012a** (CS), **Samy & ElMaraghy 2012b** (CS)
Type of buffers	**Kuzgunkaya & ElMaraghy 2006** (CS), **Samy & ElMaraghy 2012b** (CS)
State of buffers	**Kuzgunkaya & ElMaraghy 2006** (CS), **Samy & ElMaraghy 2012b** (CS)
Failure	**Kuzgunkaya & ElMaraghy 2006** (CS), **Samy & ElMaraghy 2012a** (CS), **Zhang & Tseng 2007** (CS)
No of processes	Sivadasan et al. 2002 (S), **Garbie & Shikdar 2011b** (CS), **Garbie & Shikdar 2011a** (NE), Blecker & Abdelkafi 2006, **Deshmukh et al. 1998** (NE), **Jacobs 2013, Schaffer & Schleich 2008** (CS), **Sivadasan et al. 2006** (NE)
No of production lines	**ElMaraghy et al. 2012, Wang et al. 2011, Kuzgunkaya & ElMaraghy 2006** (CS), Sivadasan et al. 2002 (S), **Garbie & Shikdar 2011b** (CS), **Garbie & Shikdar 2011a** (NE), Blecker & Abdelkafi 2006, **Deshmukh et al. 1998** (NE), **Perona & Miragliotta 2004** (CS), **Schaffer & Schleich 2008** (CS), Hayes & Clark 1985
Manufacturing strategy	**Garbie & Shikdar 2011a** (NE), Blecker & Abdelkafi 2006, Wiendahl & Scholtissek 1994, Isik 2009
Resources	**Garbie & Shikdar 2011a** (NE), **Deshmukh, Talavage, and Barash 1998**

	(NE), **Zhang & Tseng 2007** (CS)
Job shop	**Deshmukh et al. 1998** (NE), **Zhang & Tseng 2007** (CS)
Capital costs (rent/heating)	**Perona & Miragliotta 2004** (CS), **Zhang & Tseng 2007** (CS)

The table above (3-3) describes all the CCFs that are related to production. This group of processes gathers the majority of the factors, which are related to the machines and the production flow, batch sizes, change-over and set up times, but also to the assembly processes, tools and operators. It is worth mentioning that there is a high commonality (2/3) between the list of the factors that are relevant to the number of components and the list of the factors relevant to the number of finished goods. Moreover, there is information about the quantification of all the CCFs for the production and manufacturing processes and the majority is supported by empirical evidence, specifically case studies.

Table 3-4 Articles discussing "Manage logistics and warehousing"

	No of components
Transportation and handling within the production site and warehouse	**ElMaraghy et al. 2014** (CS)**, Garbie & Shikdar 2011a** (NE)**, Deshmukh et al. 1998** (NE)**, Samy and ElMaraghy 2012a** (CS), Isik 2009, **Zhang & Tseng 2007** (CS)
Product assortment in inventory	**Thyssen et al. 2006** (CS)**, Jacobs 2013**
Scrap	**Perona & Miragliotta 2004** (CS)
Location of warehouses	Hayes & Clark 1985
	No of finished goods
Product assortment in inventory	**Li 2007** (NE), Sivadasan et al. 2002 (S), **Perona & Miragliotta 2004** (CS)**, Jacobs 2013, Benjaafar et al. 2004**)
Warehouses	**Garbie & Shikdar 2011b** (CS)
Inventory	**Garbie & Shikdar 2011b** (CS)**, Perona & Miragliotta 2004** (CS)**, Foster & Gupta 1990** (CS)**, Benjaafar et al. 2004, Blecker et al. 2004**
Transportation and handling within the production site and warehouse	**Garbie & Shikdar 2011a** (NE)**, Deshmukh et al. 1998** (NE)**, Perona & Miragliotta 2004** (CS)**, Samy & ElMaraghy 2012a** (CS), Isik 2009, **Zhang & Tseng 2007** (CS)
Identification system	**Garbie & Shikdar 2011a** (NE)
Scrap	**Perona & Miragliotta 2004** (CS)
Administrative costs	**Rommel et al. 1993** (CS)**,** Wiendahl & Scholtissek 1994

Table 3-4 gathers the CCFs identified in the process of storage and distribution. The factors describe the activities of keeping components and finished goods in stock, but also handling activities within the warehouse and the production site and location of the warehouse. Moreover, the volume of the inventory and the scrap rate are described as factors that cause asymmetrical cost distribution. The identification system of the finished products that are kept in stock and the maintenance of it via administrative tasks are discussed as factors responsible for costs that are uneven among the products. All the CCFs related to distribution and warehousing from the literature study, except for the factor "Location of warehouses", are accompanied with quantification examples and supported by empirical evidence. The CCF "Location of warehouses" is only discussed without any quantification method or empirical evidence.

Table 3-5 Articles discussing "Markets, customers and capabilities"

	No of components
No of orders	**Thyssen et al. 2006** (CS)**, Perona & Miragliotta 2004** (CS), Isik 2009, **Bozarth et al. 2009** (S), **Sivadasan et al. 2006** (NE)
Order size	**Perona & Miragliotta 2004** (CS)**,** Cooper & Kaplan 1998, Isik 2009, **Bozarth et al. 2009** (S), **Sivadasan et al. 2006** (NE)
	No of finished goods
No of orders	Sivadasan et al. 2002 (S), Blecker & Abdelkafi 2006, **Perona & Miragliotta 2004** (CS)**, Rathnow 1993** (CS)**,** Wiendahl & Scholtissek 1994, Isik 2009, **Sivadasan et al. 2006** (NE)
Demand	Sivadasan et al. 2002 (S), **Garbie & Shikdar 2011a** (NE)**, Deshmukh et al.1998** (NE), Isik 2009, **Sivadasan et al. 2006** (NE)
Information flow	Sivadasan et al. 2002 (S), Isik 2009
No of customers	**Garbie & Shikdar 2011b** (CS), **Perona & Miragliotta 2004** (CS)**, Rathnow 1993** (CS), **Sivadasan et al. 2006** (NE)
Order size	**Perona & Miragliotta 2004** (CS)**,** Cooper & Kaplan 1998
Order taking process	**Blecker et al. 2004**

The last table presents the factors related to the sales process. All the factors listed above, both regarding the number of components and the number of finished goods, are internal factors that are related to complexity. Even though some of them are related to the customers and the sales processes, as discussed in the relevant literature, these factors refer to the capabilities of the company. Consequently, they are considered to be responsible for the uneven cost allocation among the products. "Information flow" is the only factor without any quantification methods discussed in the literature and the CCF "Order taking process" is not supported by empirical evidence. The rest of the CCFs identified are supported both by quantification examples and empirical evidence (CS, S, NE).

As it can be seen from the tables above, the identified CCFs are related to both the number of variants on finished goods level and number of components. Specific process steps identified are the flow of materials, variety in the production lines, machinery, warehouse and distribution, customers' service and order handling process. In detail, batch size, set up time, waiting time, tools and flow shops are the main factors related to production and machinery. With reference to supply, CCFs identified are number of customers and number of distribution centers. Logistics and warehouses gather also various CCFs, such as number and size of warehouses, locations, capacity, variability of inventory and handling processes in the warehouses. Through these factors complexity costs can be quantified.

It should be mentioned that in the literature review, some of the CCFs are quantified or/and tested in cases. In addition to that, the level of detail, regarding the quantification method and the data required vary significantly among the different articles. However, these two aspects (quantification methods and data acquisition) are not considered in this current work.

This section of the literature review answers RQI regarding identification of complexity. The results of this analysis are also presented in Papers A and G.

3.2 Quantification of complexity

Several approaches have been identified in the literature review for minimizing complexity in an organisation. Both academia and industry have contributed to this research field by either a structured approach, or by focusing on different aspects of complexity. This section discusses the existing methods for identification and quantification of complexity.

Numerous researchers (Kaplan 1994, Mariotti 2010, Zhang & Tseng 2007) have developed methods for measuring product costing. Three of them that have been more often used in the literature are discussed: Volume-Based Costing, ABC and Volume-Based Costing and Feature Costing.

Volume-Based Costing categorises all product related costs into material, direct labour and manufacturing overhead costs. This method is widely used, although it does not take into consideration the resources utilisation. Cooper (1998) demonstrates how size and volume misquote the actual product cost by numerical examples.

Based on that result Cooper and Kaplan (1998), create the ABC method, in which the cost of each object is calculated based on the consumption of activities and resources in order to be produced. A step further, Walker et. al. (1991) proposes the Volume-Based Costing and Feature Costing method for the assessment of cost allocation at product attribute level.

Kaplan and Anderson (2007) have introduced time as a dimension of ABC method. On pilot cases, they have defined the scope of their analysis on one branch and in one facility, but not an entire enterprise. In their research, several cases are described; each of them is only focusing on one aspect of complexity. The procedure suggested consists of four steps; preparation, analysis, pilot model, and rollout (Kaplan & Anderson, 2007).

Zhang and Tseng (2007) discuss a framework for assessing product profitability and cost behaviour. Four aspects are defined in order to provide a concrete method for measuring product costs: unit level (activities related to the volume of each unit), batch-level (activities related to the number of batches produced), product-sustaining (activities related to the support of product portfolio), and facility-sustaining (activities related to sustaining of the facility). They also describe another possible application of the relationships between product variety and costs is to compute or estimate each product variant's cost by taking into account the unit-level, batch-level and product-sustaining level incurred in each operation. The main limitation of this method is that products are modularized and the interfaces between modules are standardized so that changes in one module will not affect another (Zhang & Tseng, 2007).

Wilson and Perumal (2009) suggest a four - step model in order to assess the impact of complexity in three dimensions of an organization; product, process, organizational structure. The first step of the model includes selection of a case and quantification of the benefits. Then the key levers for optimization of the profit have to be identified. The third step is an immediate action of reducing the costs, and the final step is to record the cost caused by increasing complexity in all key areas and prevent it from rising again.

The Whale Curve is used to identify and illustrate the products that contribute most to the profits. When the "high-runners" are identified, complexity has to be defined. According to Wilson and Perumal (2009) variable costs, and process and production processes conceal complexity. The method for evaluation of the initiatives to reduce complexity is the quantification of the inventory returns and the return on invested capital (ROIC).

George and Wilson (2004) have been working on identifying "good" and "bad" complexity. They calculate product profitability by the following formula:

Equation 3-1:

$$\text{Economic profit} = (\text{ROIC\%}-\text{WACC\%})*\text{invested capital}$$

where, ROIC is the percentage return on invested capital and WACC is the weighted average cost of capital.

An additional formula (Equation 3-2) is used for quantification of complexity costs, while the initiatives suggested include simplifying product and service lines, assorting customer value adding complexity, and implementation of Lean principle and IT solutions.

Equation 3-2:

$$\mathrm{SCE} = \frac{[2\mathrm{V}(1 - \mathrm{X} - \mathrm{PD})]}{[\mathrm{N}(2\mathrm{A} + 1)\mathrm{S}]}$$

where V: total value-add time in the process, X: percent of products or services with quality defects, P: Processing time per unit, D: total demand of products and services, N: number of different tasks performed on an activity, A: number of activities or steps in the process, S: longest setup time in the process.

Mariotti (2008) creates a two-step approach for dealing with complexity: "Define and Solve". In order to be able to identify and measure complexity, Mariotti (2008) suggests a personalised approach. As complexity rises in several processes, the actors involved in these should understand and realise the complexity cost factors, and translate them in common terms of their work life. Then, it is possible to create a Complexity Index (CI). The CI serves as a diagnosis of all the factors possible for causing complexity, and it is based on assessments from employees in sales, finance and product development. Then, the second step of the approach is to quantify them and decide upon criteria for evaluation of the complexity levels. Pareto Principle, the 80/20 rule by measuring sales number, customer contribution, and gross margin provides the quantification of the CI. Furthermore, it is also used the method of measuring return versus complexity, to calculate the revenue (sales) and the profit margin per SKU. Finally, Marrioti (2008) names examples of initiatives and possible sources of complexity, and claims that complexity should be firstly identified and then solved.

A five step approach is introduced by Hansen et al. (2012) for calculating and assigning the cost of complexity on variant level throughout the entire product portfolio. The method consists of the following five steps: (1) scoping of the products, (2) analysis of the profitability via ABC analysis, (3) identifying the life cycle complexity factors (LCCFs), (4) scenarios for short-term complexity reduction, (5) complexity reduction program for cleaning up the product portfolio.

ElMaraghy et al. (2013) focus on strategies for managing product variety, by using the concepts of product architecture, product modularity, commonality, integration, differentiation, mass customisation and personalisation. They define internal and external complexity and suggest a quantification method based on the net value (NV), gross utility (GU), acquisition costs (AC), and evaluation costs (SEC), A set of initiatives is also suggested, firstly by measuring the variation of GU, AC and SEC and their relation to the principles of postponement, product modularization, cellular manufacturing, dynamic teaming, socio-technical system design, or system configuration design (ElMaraghy et al., 2013). A second aspect for facing complexity is robust process design. By recombining or reusing existing resources allows lower AC. The third initiative is related to the development of the solution space, by targeting on unsatisfied market need increases the GU. Finally, the minimization of choice complexity can be achieved by choice navigation capability of the manufacturer and result in reduction of SEC.

The model of Schuh et al. (2011) for classification of systems in four domains (product program, product architecture, production structure, supply chain), is also used for identification of complexity factors. They suggest the establishment of a complexity-related fit of the production system by determining the right level of standardization for each structure forming element.

Wan et al. (2012) have performed research in the combined impact of product variety on operations and sales performance. They have created guidelines, mainly for industrial practitioners, in order to cope with complexity. They claim that complexity causes an indirect effect of product variety on sales, which can be quantified by measuring operations and sales performance. For the suggested quantification method they account for the number of SKUs sold at distribution center, the number of sales, the forecasted demand, the amount of orders received and the number of returned products.

As previously discussed there is a popular theory that variety initially leads to increases in sales, as increased product variety appeals to variety-seeking consumers. However, the increases in sales are at a diminishing rate due to cannibalization as variety increases. After product variety reaches a certain “optimal” level, the indirect negative effect of product variety is realised (Wan et al., 2012). Suzue (2002) suggests a method of radical cost reduction, by implementing a reduction in half of the product parts, production processes and lead time.

Li et al. (2007) focus their research on the interaction between external and internal environment complexity, strategic and financial controls, and product and process decisions. They have several study cases from the changing business environment of China. A theoretical model of representing the interrelations among environmental complexity, management control systems, and manufacturing strategy is proposed, based on similar approaches from the existing literature (Hayes & Wheelwright 1984, Hitt et al. 1996, Simons 1994). The model provides a tool for identifying the CCFs both in internal and external environment (business and organization), relate them with strategic and financial control, and, finally, present their results on product development and manufacturing processes. They measure the impact of environmental complexity and suggest a plan for strategic change.

Hu et al (2011) examine product complexity in terms of variation and assembly systems. The formula for quantification of the total complexity is presented below.

Equation 3-3:

$$C_{system} = w_1 C_M + w_2 C_{MHS} + w_3 C_B$$

where, C_{system} is the total assembly system complexity, C_M, C_{MHS}, C_B are machine, material handling, and buffer equipment complexities respectively. Weights w_i represent the relative importance of the complexity of the three equipment classes. (Hu et al., 2011)

Several researchers (Pine 1993, Sanchez & Mahoney 1996, Ulrich 1995, Ulrich & Eppinger 1995) have outlined that complexity hinders in the high product variety and frequency of changes. Danese and Romano (2004) suggest as the solution to eliminating that complexity, the alignment of sales, production, planning and engineering activities, by the implementation of product modularization concept. Sivadasan et al. (2006) measure the operational complexity of supplier–customer systems by using mathematical modelling technics.

Gottfredson and Schwedel (2008) suggest a "Model T" approach, mainly for practitioners struggling with complexity. They firstly recommend the calculation of the cost of offering just one product, and then scaling it up by adding the cost of each additional feature every variant offers. Then second step is the identification of the true customer value adding features. Combining the results from these two steps, the company can avoid the expansion of SKUs, by covering all needs with existing products. In other terms, it is a method of customer-based substitution. They suggest a three step approach for dealing with complexity in an organization. First complexity costs should be calculated with the "Model T" method. Then, customers truly value has to be identified. This can be achieved through surveys. Finally, by keeping the business model simple and implement pruning among the products complexity can be eliminated.

Forza and Salvador (2002b) have been working on diagnosing complexity of product information in relation to implementation of configuration systems. The following aspects have been identified: Product variant design and engineering, and production. The implementation of product configuration system in environments with high product variety is suggested.

Five sources of complexity have been identified by Prasad (1998); inherent product complexity, process complexity, team co-operation and communication complexity, computer and network complexity, and a maze of specifications including international regulations and safety. Prasad (1998) also discusses variety costs, taking into consideration the number of options in a product variety, how much the product is away from its finish, how "painful" it is to change from one variety to another. The formula for quantification of the complexity index suggested is described below.

Equation 3-4:

$$C_v = \prod_{i=1}^{i=3} (a_i)$$

Equation 3-5:

$$\begin{aligned} Cost\ of\ variety \\ &= minimum\ \ cost\ of manufacturing\ an\ assembly * (1 - C_v) \\ &+ maximum\ cost\ of\ manufacturing\ an\ assembly * C_v \end{aligned}$$

where a_i is the number of options, time, or change-over efforts.

Information-theoretic methods are developed for assessing complexity in manufacturing systems (Frizelle & Woodcock 1995, Efsthiou et al. 2002). Complexity, categorized as structural and dynamic, can is quantified by entropic measures (Sivadasan et al. 2002, Sivadasan et al. 2006, Wu et al. 2007).

3.3 Complexity reduction

The main concepts identified addressing complexity reduction are drawing attention to reduction of product complexity, with methods such as component substitution and product standardization (Marti 2007, Suzue & Kohdate 1990, Jiao et al. 2007). Other approaches are directed towards process complexity, including more efficient inventory management by reducing the number of variants kept in stock (Brun and Zorzini, 2009), optimization of the production process (Ramdas 2009, De Groote 1994) and process standardization by utilizing a PCS (Forza & Salvador 2002, Haug et al. 2011, Hvam 2013). Identification of a more efficient production strategy and process segmentation to distinguish between production and handling of configure to order (CTO), MTO and ETO products is also discussed (Rudberg & Wikner, 2004). The different methods for complexity reduction cover elements from both monetary and non-monetary initiatives, indicating a dichotomy of the topic. (Geraldi et al., 2011).

The methods suggested regarding reducing product complexity focus on increasing the overview and transparency of the product assortment (Suzue & Kohdate, 1990) and improving product standardization (Jiao et al., 2007). Improvements on the product's architecture via its structural properties can be achieved through strategies of enhancing modularization, standardization and commonality (Kreimeyer & Lindemann, 2011). Efstathiou et al. (2002) develop a tool based on entropic-measured approach for quantifying the decision-making complexity of the manufacturing systems. Regarding methods for reduction of process complexity, optimization of the different lifecycle processes is discussed, in areas such as supplier-customer relationship (Jiao et al., 2007), manufacturing process (Frizelle & Woodcock, 1995), production process (De Groote 1994, Ramdas 2009) and distribution (Wan et al., 2012). Blecker et al. (2004) suggests mass customization as a strategy for eliminating complexity caused by increasing variation in product architecture, inventory and order taking process. A detailed overview over related complexity measures for single products can also be found in Sinha and de Weck (2013).

The following sections (3.3.1, 3.3.2 and 3.3.3) present the existing literature on complexity reduction and elaborate on the concepts of production strategy, substitution and implementation of PCSs.

3.3.1 Production strategy

3.3.1.1 Product customization with global supply chain networks

To compete on international markets, manufacturing companies are organizing their business processes around a global supply chain network (Makhija et al., 1997). Figure 3-5 displays a conceptual model of a hypothetical supply chain network design. From a high-level perspective, supply chains may typically include activities related to engineering and purchasing, manufacturing, assembly, distribution and sales. To serve the needs of local markets, traditionally these activities have in their simplest form been stablished within the country of origin. With globalization firms have over time been moving towards international markets, for which some of the supply chain requires to be outsourced or physically displayed (Kumar et al., 2010). As indicated in Figure 3-2, depending on the sales strategy, to secure lead times and product delivery, sales may for example be displaced to target markets, thereby establishing local sales channels. To lower product costs or to focus on key competences, manufacturing on the other hand may be outsourced or displaced to low cost countries, keeping the final assembly of components in the country of origin (Kusaba et al., 2011). An example of this approach can be seen in the apparel industry, where products are designed in the country of origin, often manufactured in others, and sold locally within target markets (Kumar and Arbi, 2008). In more general terms, the relative cost advantage of low cost countries and the small value added to the final products is often named to be the main motivation for emphasizing this particular part of the supply chain, like manufacturing (Fredriksson and Jonsson, 2009). To this end, several studies have investigated the possible gains and motivation from reconfiguring supply chain networks. While major part of the research suggests an overall positive effect on the firm's performance, few studies also point out the potential risks with this strategy (Horn et al., 2013).

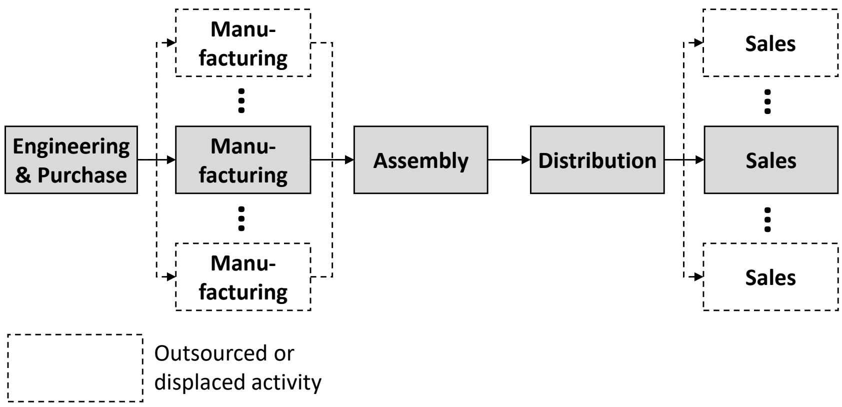


Figure 3-5 Conceptual global supply chain network with outsourced or displayed manufacturing and sales (Bonev et al. 2015)

In addition to the network design of a particular supply chain, offering product customization requires consideration about the product design and production planning and control system. The degree to which customization is provided can vary across the entire product portfolio of a company and is often described through the relative involvement of customers with the companies' supply chain, i.e. to the customer order decoupling point (CODP) (Duray, 2002). As displayed in Figure 3-6, the more supply chain activities are directly related to a particular customer order, the higher is the degree of the offered variety and the early in the supply chain the CODP is placed. Literature names a few distinct product planning and control systems allowing for customization, depending on the relative placement of the CODP (Rudberg and Wikner, 2004). In an ETO situation, components have to be engineered based on a specific request from customers, forcing all subsequent activities to be directly engaged in fulfilling the order. Due to the early customer involvement, typically ETO products obtain a large amount of variety, but their production volumes are low (Caron and Fiore, 1995). In a MTO scenario, pre-designed and available components are used for manufacturing and subsequent assembly of the product variants. In case both engineering and manufacturing activities are performed based on forecast, sub-assemblies from stock are used in the assembly process to ATO the requested product variant. To account for a high amount of final variety, a modular product design has been reported to facilitate the separation between manufacturing of components and (final) assembly (Kusiak, 2002). With the so called modular product architecture, components or modules can to be produced or outsourced based on forecast and recombined according to the requirements of the customer (Mikkola, 2007). This would allow the company to postpone the CODP closer towards the customer, i.e. to a MTO or ATO situation. The so called Type-III postponement strategy aims at capitalizing on standardization and modularity, thereby achieving economies of scale (Forza et al., 2008).

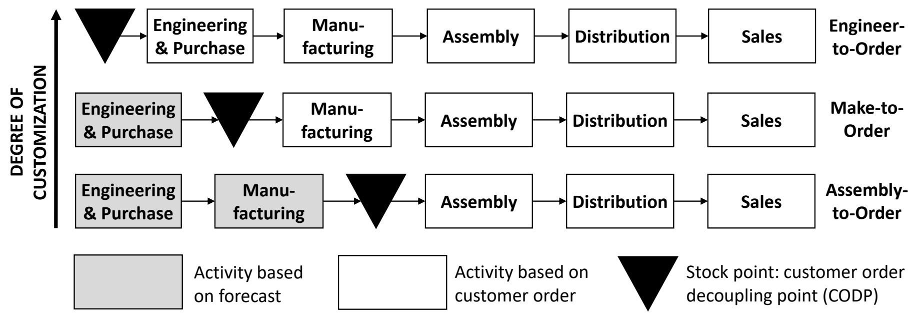


Figure 3-6 Degree of customization and placement of the CODP (Bonev et al. 2015)

3.3.1.2 Supply chain performance and reconfiguration

Despite the rather simplistic view on the production process, dividing the different production planning and control systems according to the placement of the CODP helps to define clear strategies for a particular supply chain network design. Decisions about a suitable configuration of the network may be related to key operational performance measures of a company, such as to cost and time (Neely et al., 2005). From customers perspective, higher degree of customization allows for more engagement in the supply chain and hence to more unique product designs. However, since more activities have to be performed after a specific order has been placed, there is a trade-off between the uniqueness of the product design and the related delivery time and cost. In general, the higher the number of activities performed for a customer, the bigger the sum of the individual lead times of each process (Piller et al., 2004). Moreover, unique designs with higher engineering engagement have often proved to be more costly and less quality assured (Ulrikkeholm & Hvam, 2014). Since a higher percentage of the supply chain is performed based on a distinctive customer requirement, processes are less standardized and may involve ad hoc and unproven tasks which require stronger coordination effort (Caron & Fiore, 1995). On the other hand, with an MTO and ATO strategy, the increased standardization of components and processes combined with reduced delivery times has shown to be particularly useful for products with moderate or limited variety and high volumes (Duray, 2002). Therefore, setting the right strategy for the production planning and control system can have a wide-ranging impact on the profitability of the provided portfolio.

Traditionally, decisions about the placement of the CODP are made based on inventory management theories and may include aspects of inventory cost, lead time requirements towards the market, sales volume and order frequency, and scope of offered variety (de Koster et al. 2007, Toni et al. 1988). Accordingly, items with low volumes and high variety should be organized around an early placement of the CODP and vice versa. Recent literature however emphasizes that more and diverse customization significantly increases supply chain complexity, making cost allocation and prices estimations less accurate (Bozarth et al., 2009). Planning with higher product variety often leads to overestimated profits, where the complexity-induced cost of the supply chain are not taken appropriately into account by traditional accounting methods (Cooper, 1993). Schuh et al. (2008) discuss complexity from two forces (Schuh et al., 2008). External complexity occurs due to desired customer requirements. This defines the number of the offered product variety. Internal complexity describes the processes, parts and product designs across supply chain needed to provide the demanded product variety. Reducing the internal complexity as much as possible by obtaining the necessary external complexity is seen as a guiding principle for managing the complexity across supply chains (ElMaraghy et al., 2013).

A common way to identify unnecessary external complexity is to investigate the realized CMs for each variant according to the pareto principle (Pareto, 1971). As studies have shown, in complex supply chains a large amount of the sold variants do not contribute if at all to the turnover of firms. Instead, a major part of the turnover is generated from a small amount of the variety (Brynjolfsson et al., 2011). In order to classify which variants to keep and which to reduce or replace, a categorization into A, B, and C products is typically performed (Yücel et al., 2009). Once unprofitable variants are identified, various initiatives can be enforced to reduce the related complexity. Depending on the product design and the supply chain network, such initiatives may include the increase of modularity (Gualandris & Kalchschmidt, 2013), postponement (Trentin et al., 2011), or product standardization through increasing component commonality (Labro, 2004).

3.3.2 Product standardization

3.3.2.1 Product substitution

Substitution is a method which complies with Mass customization principles and platform designs. Garud and Kumaraswamy (1995) describe as "economies of substitution" the manufacturing strategy that companies apply, regarding reusability of components within a company's product range. Ye (2014) categorizes substitution into two classes: vertical and horizontal (Figure 3-7). Vertical substitution can be one-way, where the product of higher quality or value can substitute a product of lower quality or value (Hsu et al. 2005, Smith & Agrawal 2000), or two-way, where products of both higher and lower can substitute each other (Xu et al., 2011). Horizontal substitution can be distinguished between centralized and decentralized. Current research refers to this classification as firm-driven (centralized) and customer-driven (decentralized). This research is primarily focus on two-way firm-drive substitution at a module level, as the customer-driven substitution cannot be controlled. The sales person, or even the customer himself, decides on the substitution of one final product with another (Zhou & Sun, 2013).

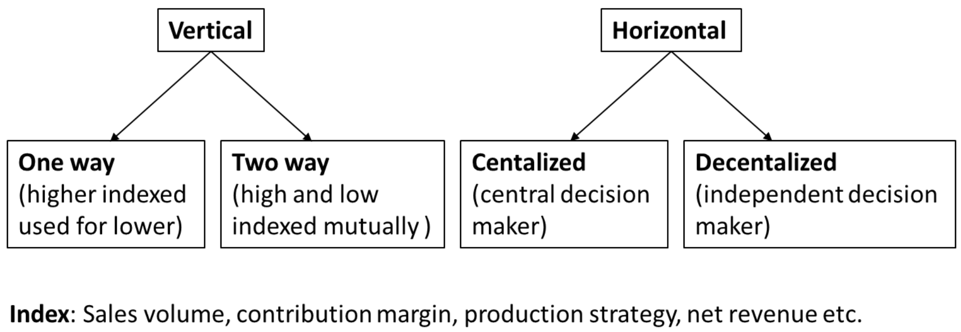


Figure 3-7 Substitution categorization (Bonev et al. 2015)

Zhou and Sun (2013) have developed a model to determine the optimal component quantities in an ATO system with component substitution, so as to maximize manufacture's profitability. They consider firm-driven component substitution due to lack of inventory and production cost, distribution cost and revenue loss are the parameter to be taken into account. Rao et al. (2004) develop a model to estimate the specific products to be produced, their quantities and how these products can satisfy the demand. Costs that are taken into consideration in the model cover setups, production, overage, stock out and substitution. This refers to one-way downward substitution, where the demand of a certain product can be satisfied by a specific range of products. The impact of product substitutability on optimal capacity and flexibility is discussed by Lus and Muriel (2009), where they also consider pricing, as aspects to be taken into account when planning the product assortment.

Several researchers have considered product substitution based on the demand. Yaman (2009) creates a model in order to define the lot sizing problem by substituting the products of low quality with high quality products. On the other hand, Hsu et al., (2005) develops algorithms in order to define the lot size between two products. The product in lower demand can substitute the product higher demand, with or without the need for redesign.

3.3.3 Product configuration systems

In this section, a literature review is performed in the research area of PCSs. The focus of the literature review is identifying the main benefits and challenges of implementing and utilizing PCSs. Several research groups have conducted extensive studies in this field.

3.3.3.1 Benefits

First, the benefits identified by utilizing a PCS are discussed. As the focus of this study was to assess the impact of implementing a PCS, quantitative data were required. The results from the literature study are presented in Table 3-9. The benefits discussed in the literature are listed, and the articles discussing the benefits are listed in the second column. The last column specifies whether the impact of the utilization of a PCS was measured and shows quantitative data from the benefits identified

Table 3-6 Benefits obtained from implementing PCSs.

Benefit	Authors	Measurement
Reduction in lead time for making specifications	Forza & Salvador 2002a, Hvam 2006, Hvam et al. 2004, Heatley 1995, Hvam et al. 2011, Forza & Salvador 2002b, Aldanondo et al. 2000, Haug et al. 2011, Ardissono et al. 2003, Ariano & Dagnino 1996	From 5–6 days to 1 day (Forza & Salvador 2002) The real working time for preparing offers and production instructions is near zero (Hvam 2006) 75–99.9 % reduction in the quotation lead time (Haug et al. 2011) 15–25 days to 1–2 days (Hvam et al. 2004)
Reduction in lead time for delivering the product	Hvam 2006, Hvam et al. 2011, Ardissono et al. 2003, Ariano & Dagnino 1996, Petersen 2007, Sviokla 1990	Delivery time reduced from 11–41 days to 1 day (Hvam 2006)
Saved work-hours	Forza & Salvador 2002a, Forza & Salvador 2002b, Hvam et al. 2004, Ardissono et al. 2003, Ariano & Dagnino 1996, Heiskala et al. 2005, Petersen 2007, Sviokla 1990	The engineering hours for creating quotations were reduced from 5 work-weeks to 1 to 2 work-days (Hvam et al. 2004) Throughput cycle was reduced from 6 days to 1 day (Heiskala et al. 2005)
Increased quality of product information/specifications	Forza & Salvador 2008, Barker et al. 1989, Slater 1999, Forza & Salvador 2002a, Forza & Salvador 2002b, Hvam et al. 2004, Heatley 1995, Hvam et al. 2011, Tiihonen et al. 1996, Ardissono et al. 2003, Ariano & Dagnino 1996, Heiskala et al. 2005, Sviokla 1990, Yu & Skovgaard 1998)	Reduction to almost zero of errors in configurations released by the sales office (Cipriano Forza & Salvador 2002) Increased level of correctness of product information to almost 100% (Forza & Salvador 2002) Specifications quality improved from 60% to 100% manufacturable (Heiskala et al. 2005)
Improved product quality	Trentin et al. 2012, Barker et al. 1989	N/A
Improved on-time delivery	Tenhiälä & Ketokivi 2012, Forza & Salvador 2002a, Forza & Salvador 2002b	N/A
Increased employee productivity	Forza & Salvador 2002a, Hvam et al. 2011, Slater 1999	N/A
Lower production costs	Hvam 2006, Barker et al. 1989	Fixed production costs were reduced by 50% and variable costs by 30% (Hvam 2006) Reduction from 30% to less than 2% in the number of assembly errors

		(Hvam 2006)
Improved efficiency in aftersales	Hvam 2006	Time for replacement was reduced from 5–6 hours to 20–30 minutes (Hvam 2006)
Improved knowledge management	Gronalt et al. 2007, Forza & Salvador 2002, Hvam 2006, Tiihonen et al. 1996, Slater 1999	N/A
Improved control of product variants	Forza & Salvador 2002a, Forza & Salvador 2002b, Forza & Salvador 2008, Tenhiälä & Ketokivi 2012	N/A
Reduced product lifecycle cost	Fleischanderl et al. 1998	PCS supporting the complete configuration process may reduce the configuration cost up to 60% over the product lifecycle (Fleischanderl et al. 1998)
Increased customer satisfaction	Barker et al. 1989	N/A
Improved customer relationships/communications	Forza & Salvador 2002a, Forza & Salvador 2002b, Heatley 1995, Forza & Salvador 2008, Slater 1999, Gronalt et al. 2007	N/A

Summarizing the findings from the literature review, the implementation of a PCS provides various benefits to companies, in terms of resource reduction, decreased lead time, better communication with customers and improved product quality (Table 3-9).

There is a lack of empirical evidence that measured the impact of implementing PCSs on improved profitability and more accurate cost estimates. The present work contributes to the literature by providing a longitudinal field study that compared the economic performance of the products and the accuracy of the cost calculations before and 4 years after a PCS was implemented in an industrial manufacturing company.

3.3.3.1.1 Benefits from using PCSs on product lifecycle processes

In this section the benefits from the utilization of a PCS identified in the literature are discussed and grouped according to different lifecycle processes.

PCSs have been implemented widely to support the specification process for the customized products and guide the sales process (Zhang 2014a, Gronalt et al. 2007, Slater 1999). The benefits from applying PCSs can be described in terms of shorter-lead time and improved quality of the product's specifications, reduced resource consumption and increased customer satisfaction (Hvam et al. 2008). For that reason, less rework and less iterations are required, as the quality and the accuracy of quotations are increased (Hvam et al. 2004). Furthermore, PCSs can be used as tools that support sales persons to offer customized products within the boundaries of standard product architectures and thereby enable companies to be more in control of their product assortment (Forza & Salvador 2002a, Fleischanderl et al. 1998).

In order to achieve the benefits from a mass customization approach, utilization of PCSs and standardization of the product's architecture are considered as the main enablers (Pine II et al. 1993, Piller & Blazek 2014). The growing product variety at the companies has led to an increasing complexity of products and processes and to the need of better coordination of the way product specifications are performed (Forza & Salvador 2007). PCS are used to support the product configuration processes, which consist of a set of activates that involves gathering information from customers and generation of all required product specifications (Forza & Salvador 2002a, Forza & Salvador 2007). In PCSs a set of components along with their connections are pre-defined and where constrains are used to prevent infeasible configurations (Felfernig et al. 2000).

Companies utilizing PCSs have achieved increased ability to manage product variety, improved product quality, simplification of the customer order process and complexity reduction (Zhang et al. 2013, Trentin et al. 2012, Forza & Salvador 2002a, Salvador & Forza 2004). Furthermore, preservation of knowledge, use of fewer resources, optimization of products designs, less routine work, improved certainty of delivery, reduced time for training new employees and increased customer satisfaction (Hvam et al. 2008, Piller et al. 2004, Felfernig et al. 2000, Ardissono et al. 2003, Kropsu-Vehkapera 2011, Zhang 2014b, Forza & Salvador 2007) have been reported in the literature as benefits achieved via the use of a PCS. In addition, when the complete configuration process is supported by a PCS, the configuration cost may reduce up to 60% over the product lifecycle (Fleischanderl et al. 1998). On the other hand, by utilizing a PCS companies can increase sales of more standardized products and become more in control of their product range, which can lead to higher efficiency, improved quality, and reduce the product complexity (Forza & Salvador 2002a).

The following table (3-10) demonstrates these benefits according to the different life cycle processes.

Table 3-7 Summary of PCS's benefits on life cycle processes

Life cycle process	Benefit
Sales	Reduction in quotation lead time (Haug et al. 2011) Increase customer satisfaction (Barker et al. 1989) Improved communication and relationship with customers (Forza & Salvador 2002a, Forza & Salvador 2002, Heatley 1995, Forza & Salvador 2008, Slater 1999, Gronalt et al. 2007) Improved control of product portfolio (Forza & Salvador 2002a, Forza & Salvador 2002, Forza & Salvador 2008, Tenhiälä & Ketokivi 2012)
Engineering	Reduction in lead time for preparing specifications (Hvam 2006) Increased quality of specifications (less errors) (Forza & Salvador 2002b)
Production	Reduction in work hours (Hvam et al. 2004, Heiskala et al. 2005) Reduction in hours making production instructions (Hvam 2006) Improved quality and number of specifications that can be used directly without iterations (Forza & Salvador 2007, Heiskala et al. 2005)
Distribution	Reduction in delivery time (Hvam 2006) Improved on-time delivery (Forza & Salvador 2002a, Forza & Salvador 2002, Tenhiälä & Ketokivi 2012)
Installation	Reduction in number of errors (Hvam 2006)
After-sales	Improved efficiency (Hvam 2006)

3.3.3.2 Challenges of implementing a PCS

In this section, the literature focuses on the challenges and practical implications of implementing PCSs. The challenges refer not only to the scope of the PCS but also to the implementation and utilization of the system by employees and its acceptance as part of their daily work routine. The following table (3-11) summarizes the main challenges identified in the literature.

Table 3-8 Challenges associated with utilizing PCSs.

Challenges	Authors
Supporting customers' needs in the configuration process	Blecker et al. 2004, Fleischanderl et al. 1998
Product modeling and data acquisition	Forza & Salvador 2002, Forza & Salvador 2002, Tiihonen et al. 1996, Fleischanderl et al. 1998)
Errors in the configuration process	Tiihonen et al. 1996
Documentation and maintenance configuration model	Forza & Salvador 2002, Tiihonen et al. 1996
Change management	Forza & Salvador 2002

The implementation of PCSs are not free of challenges during the process. This is explained in the difficulties faced by the users and the developers of PCSs related to supporting customers' needs in the configuration process, product modeling and data acquisition, errors in the configuration process, documentation and maintenance and challenges regarding change management and acceptance of the system as part of the work procedures.

3.4 Summary of the theory in complexity management

This chapter elaborates on the existing approaches in the field of complexity management. In order to compare and assess the existing theories this section summaries the discussed literature in terms of profitability analysis, complexity identification, quantification and reduction.

Product profitability has been discussed in more detail by researchers. The methods for ABC product analysis has been further developed, including parameters such as time, volume, direct and indirect costs, and customers' analysis. However the suggested approaches may require significant amounts of data and the analysis may be work intensive. When it comes to complexity cost factors, existing literature suggests metrics for quantifications on a high level of abstraction.

With reference to the identification of complexity, the existing literature provides examples of pilot cases. However, it is not described in detail what is the aim of the analysis in each case and how to retrieve and verify data used. It could be claimed that there is a lack of a concrete set of criteria for scoping products and processes for complexity analysis.

Complexity has been discussed in general terms related to different levels in the organization, product strategy, supply chain set up etc. Quantification methods identified mainly cover assessment of complexity on an overall level, and the data needed and validity of the quantification are not discussed in detail.

To sum up, the previously discussed literature may vary in terms of methodology and scope. However, this review reveals that there is a common ground to the different approaches regarding portfolio management and product strategy. It has been identified that profitability analysis may be expressed differently, but it is a part of the development of a product strategy. In addition to that, several factors that are taken into consideration in portfolio management have been presented. Sales, customers and competitors are the factors that are met more frequently in the literature. However, in the literature studied no examples were found regarding how to assess the profitability of configurable products including technical assessment of product features, profitability, market aspects, competitors and an internal cost profile. This research focuses on developing an operational approach on identifying CCFs and initiatives for reduction of complexity within the manufacturing industry.

4 CASE STUDIES

4.1 Selection of companies

Case research is used as the main method. There are 12 projects with different companies in complexity management; 11 projects are conducted as CS and one as a longitudinal CS, The goal is to use multiple cases, in order to achieve external validity and ensure objectivity against emerging bias.

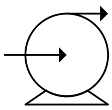
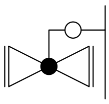
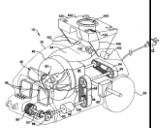
The main unit of analysis is small- and medium-sized enterprises in the manufacturing industry of ATO, MTO and ETO products in the Nordic region. Apart from the above mentioned criteria for selecting the case studies, there are additional principles for a company to be engaged in the research project, which are described in section 2.5.2. The purpose of these criteria is to enable generalization of the emergent theory within certain limits, and ensure that the cases and the conceptual framework are compatible.

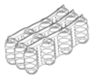
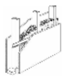
Since full access to detailed data within each company is provided, validity of the research findings can be created through an in-depth investigation. To enable a comparison across the studies and thus to achieve external validity (Yin, 2003), each case study follows the same research protocol. Accuracy of data collection is insured through foregoing qualitative methods (e.g. unstructured and semi-structured interviews) with the persons involved in each project. Then, quantitative data is collected and analyzed by means of the proposed methodology.

In every case study, there are multiple levels of analysis, as complexity arises both in products and processes in the entire value chain. From market requirements to product development, from component inventory and production to finished goods and distribution centers, are areas in which complexity has to be identified and quantified, as it is discussed in the literature review section.

The following table presents an overview of the 12 case companies involved in this research project. To ensure the anonymity of the case companies, the Latin numbers are used instead of the name. The remaining columns gather information regarding the characteristics of the companies that are relevant for this research project and the focus area of each investigation with reference to the RQs.. The last column refers to the time frame within a particular case study. For example, "5 months" indicate that the collaboration with the company lasted five months with respect to the specific investigation.

Table 4-1 Overview of the case companies

Case company	**Product / Industrial sector**	**Production Strategy**	**Business**	**Market**	**Research focus**	**Duration**
I 	Mechanical, Electrical	ATO / MTO	Professional / Consumer	Global	RQ I – RQ III	5 months
II 	Mechanical, Electrical	ATO / MTO / ETO	Professional	Global	RQ I – RQ III	5 months
III 	Mechanical, Electrical	ATO / MTO	Professional	Global	RQ I – RQ III	5 months
IV 	Mechanical / Electrical	ATO	Consumer	Global	RQ I – RQ III	5 months
V 	Building systems	ATO / MTO	Professional / Consumer	Global	RQ I – RQ III	5 months
VI	Commercial goods	ATO / MTO	Consumer	Global	RQ I – RQ III	5 months

						
VII 	Commercial goods	ATO / MTO	Professional	Local	RQ I – RQ III	5 months
VIII 	Building systems	ATO	Consumer	Global	RQ II	4 months
IX 	Mechanical / Electrical	ATO	Professional	Global	RQ III	4 months
X 	Mechanical / Electrical	ATO / MTO / ETO	Professional	Global / Local	RQ III	6 months
XI 	Building systems	ATO / MTO	Professional	Local	RQ III	6 months (in total 5 years)
XII 	Mechanical / Electrical	MTO / ETO	Professional	Global	RQ II – RQ III	6 months

4.2 Set up of case studies

The companies that provide empirical evidence to this PhD research have several characteristics. The following section introduces the companies and the set up as they were performed in each study and included in the published articles.

4.2.1 Study 1: Complexity Cost Factors – Case companies I - VII

In order to test the factors identified and provide empirical evidence, the complexity costs have been analyzed in seven manufacturing companies (I, II, III, IV, V, VI, VII). All companies are in the manufacturing industry and produce ATO, MTO, or/and ETO products. The companies produce different products and differ in size. The reason for selecting these companies with such diversity is to compare the CCFs across organizations and to get a better understanding in tandem with setting the limitations of this research.

The selected companies vary in size and type of products they manufacture, as it can be seen in table 4-1. The unit of analysis is the set of final product variants that the companies offer to their customers. In order to ensure consistency among the different cases, all data is obtained from the ERP systems. The data is also discussed with the project managers, so as to certify that the research team has all the information needed and that the data acquired is up-to-date. Moreover, a research protocol is developed and followed in all cases, regarding data retrieval and processing, in order to ensure external validity of the research.

4.2.2 Study 2: Managing complexity of product mix and production flow - Case company VIII

In order to test the proposed framework and quantify the production flow optimization by adapting the product assortment, a case study of a manufacturer in the ATO industry is performed. The company produces plaster gypsum boards for the construction industry. The final product consists of several layers (components): plaster façade (with or without paint), gypsum board, light reinforcement, heat and fire insulation. The challenging aspect of this specific case study is the lack of expanding options, especially on large scale such as expansion of the production site or the warehouse, purchase of supplementary machinery. There is limited available space in the production facility, which corresponds to a small machine or a new stock point for products in small volume. As a result the chosen case study is selected as an example where the optimization of production flow and capacity utilization could only be achieved by the examined proposition.

4.2.3 Study 3: Operational method for managing product variety - Case company IX

For the case study an ATO company in the heating and ventilation industry is chosen. The company has been operating for approximately 45 years within a global network of more than 40 countries, and its products are designed and produced in Denmark. It employees around 550 persons, and it has an annual turnover of 750 million Danish kroners (approximately 100 m€). In recent years, the company has been facing a decreasing number of sales in the main product family of its portfolio along with declining revenue. That is an additional reason regarding the selection of this company as the decrease in sales is an indication for possible underlying complexity. All data used for the analysis and calculations were acquired from the electronic database of the company.

4.2.4 Study 4: Reconfiguring variety, profitability and postponement for product customization with global supply chains - Case company X

The suggested methodology is applied on a case study of a Danish manufacturer of pumps. The company produces standardized as well as more specialized products with an ATO, MTO or ETO strategy. The main market requirements for pumps are reliability, functionality, design, price, delivery performance and solution flexibility. The product portfolio of the company includes pumps for chemical, environmental, heavy and petrochemical duty and for general purpose. The data collection is performed through the company's internal database and includes BOMs, total cost, NR, sales volume, production strategy, and country of production and distribution, on finished good level. The sample size refers to sales within a two-year period (2012, 2013). Semi-structured interviews with project managers are performed, in order to verify the accuracy of the data acquisition.

As suggested in literature, since part of the supply chain is based on forecast, the ATO products have relatively shorter lead times and better delivery performances. MTO products are produced based on an order received from the distribution center. They consist of standard parts, which additionally require special treatment, and are produced in low runs. Before their components can be produced, BOM and prices have to be verified, which results in longer lead times compared to the ATO variants. Special customer requirements are treated as ETO products and hence obtain longer lead times and higher cost in comparison to the ATO and MTO products. A significant difference between an MTO and an ETO product is that for the latter a dedicated production set-up is required, which involves alternative processes and tooling. Moreover, the R&D department is also involved in the enquiry and quotation process, to verify the feasibility of the customer's requirements and to ensure the supply chain capabilities.

The company acquires two production sites, one in Denmark and one in China, and three distribution centers (DCs), one in each of the following countries: Denmark, China and the USA. The DCs in China and Denmark deliver products produced to the respective site; the North America market is supplied by either China or Denmark. However, the products distributed in Denmark are produced in two ways; either they are entirely produced in Denmark (local), or they are produced as standard semi-finished units (SFU) in China and then the final configuration and testing is performed in Denmark.

For all of the mentioned before, this company makes a suitable candidate for investigating existing complexity and testing methods for reduction.

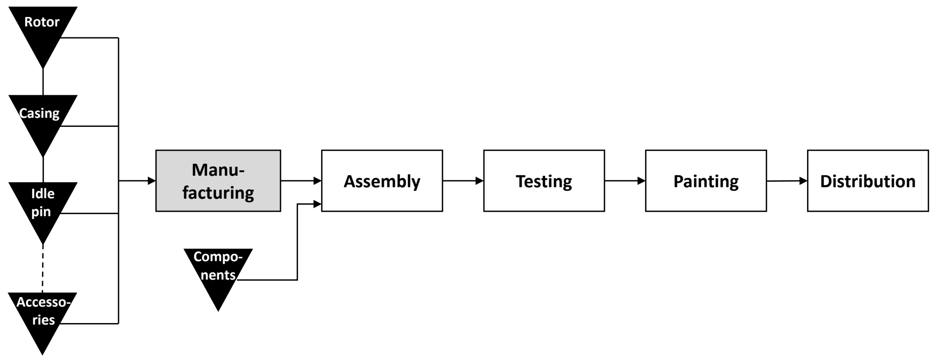


Figure 4-1 Local production in Denmark

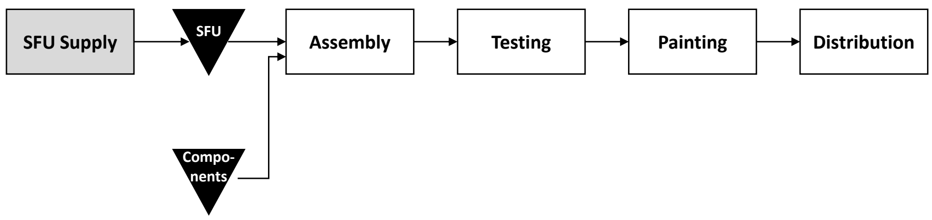


Figure 4-2 SFU production in China and final configuration in Denmark

The sample size focuses on one representative product family consisting of 299 variants, the heavy duty (HD) pumps consisting of a modular product architecture. The particular product family is selected due to its significant share of the total sales, which accounts for 60,61% of the total revenue. Moreover, HD pumps are offered based on all three production strategies with a distribution of 32%, 33% and 34% between ATO, MTO and ETO accordingly. To limit the scope of analysis, the sample size refers to products being sold from the DC in Denmark.

4.2.5 Study 5: Impact of product configuration systems on product profitability and costing accuracy - Case company XI

The case company analyzed in this study is a Scandinavian company in the building industry, which manufactures pre-made structural elements for buildings and provides installation services. The company is highly representative as a medium-sized company, which includes manufacturing, installation and maintenance in its business processes. In 2014, the company had around 100 employees and yearly turnover of approximately €17 million. In that year, the company sold 168 projects, and the average turnover per project was therefore €106,158. The company's product portfolio consists of six product families, of which five are standard products and one special.

In 2009, the process of generating quotations in the sales phase and the accuracy of the cost calculations were analyzed. The analysis revealed that the company's methods for accurately calculating costs were inadequate and affected the products' profitability. The results also indicated that the company's current procedure of using Excel spreadsheets to calculate the costs led to numerous errors, which were traced back to human mistakes. Based on this initial analysis, the company decided to invest €150,000 in order to develop a PCS to improve the process of generating quotations in the sales phase. The PCS used at the company was commercial configuration software, which builds on constraint propagation.

The PCS was developed from 2009 to 2010, and by the beginning of 2011, the company had developed a PCS able to handle most of the quotations in the sales phase. Only special products, which are categorized as non-standard solutions or engineered solutions, were not included in the system. Although the company developed and implemented a PCS to support the sales process, organizational resistance to using the system and changing current work procedures resulted in some salespersons still using the Excel spreadsheets to calculate costs for the quotations in the sales phase.

In this study, the impact of utilizing the PCS on the company's ability to make accurate price estimates for the quotations and product profitability was assessed. First, the company's overall performance is analyzed before the system was implemented in 2009 and 4 years after the implementation during the 2011–2014 period. Then the accuracy of the cost calculations and products' profitability in the quotations generated by using the Excel spreadsheets and the PCS were compared.

4.2.6 Study 6: Impact of the utilization of a product configuration system on product's life cycle complexity - Case company XII

The company selected as a case study in order to test the suggested proposition is an ETO manufacturer in the oil and gas industry. The company provides single equipment and complete systems and services and it operates worldwide. This specific company is chosen as a case study to be further investigated as it is considered to be highly representative in the engineering industry, so replication of the research could be ensured.

Data collection includes the cost for all the complete systems (projects) and single equipment (products) sold over a four-year period. The unit of analysis is the number of sales including projects and products. The related costs refer to the different phases of the products lifecycle, such as sales, engineering, production, distribution, installation and after-sales. Data were obtained through the company's internal database and verified by specialists within the company (project managers).

In detail, the different cost categories that are taken into consideration for the analysis are the following: inventory, material, engineering, production, assembly, outsourced parts and services, installation. The inventory cost and production account for more than 50% of the total cost both for projects and single products. The cost of engineering for the projects varies from 10% to 20% of the total cost, while for single products is 6%. These two cost groups account for the largest share of the total cost.

In the four-year time period, the company sold 12 projects and 193 single products. Based on the data acquired, the revenue for the projects is 743,5 m€ and for the single products

46,5 m€. Respectively, the costs are 758,7 m€ for the projects and 30,9 m€ for the single products. It can be seen from the numbers above that even though the projects create higher revenue compared to the sales of single equipment, the related costs are even higher, resulting in loss for the company. Furthermore, for the projects sold a deviation is identified between the estimated cost and revenue at the beginning of the project, when the budget is calculated, and the actual ones, when the project is finished.

These deviations can be due to external factors, such as currency, fluctuation on material price and labor cost. However, there are internal factors that also influence the increase of the estimated cost and revenue, and they need to be further investigated.

To this end, an area of interest identified during the analysis of the financial performance of the projects is the reduction of cost through repetition. When a project is re-produced based on an existing one, several cost categories are identified to have noteworthy reductions.

Engineering costs, which are calculated based on the hours spent for each project or product, seem to benefit from re-using existing documentation. The following figure illustrates the amount of hours spent on engineering for the pioneer project and for the projects reusing parts.

4.3 Developed methods and frameworks

The following section describes the developed method for addressing the RQs. The first section discusses the framework for analysing the relationship between product and process complexity. The developed framework is explained in this section and is also presented in Paper H. The second section presents the method for managing product complexity. This method is also presented in Paper C.

4.3.1 Managing complexity in product mix and production flow

4.3.1.1.1 ABC product categorization

Based on the Pareto theory (Pareto, 1971), an ABC analysis on component level is performed, where the sales volume of finished products is used to differentiate between the categories. In detail, 80% of the sales correspond to fewer products, which are considered as A products. Similarly, 15% of the sales volume corresponds to the B products and 5% to the C products.

Sales values are often stored on a final product level. To be able to perform the ABC categorization on components level the variance decomposition structure is used. Each finished product is broken into its different components, based on the listed BOM. The sales volume of the finished product indicates whether the product is A, B, or C. Through the variance decomposition analysis, the sales volume of the components is set in relation to the sales volume of the finished product.

The variant categorization is to be further used in order to implement the two-way substitution.

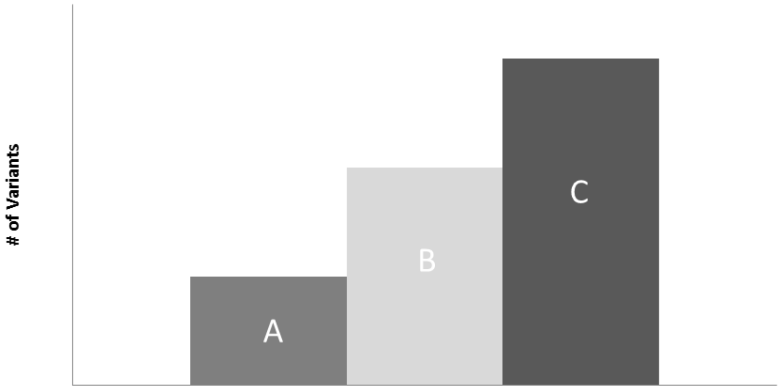


Figure 4-3 ABC analysis on component level

4.3.1.1.2 Substitution and process flow

The second aim of the research methodology is to implement a substitution method in order to measure the impact on the machine and stock utilization, which is related to the lot size. The suggested approach is based on the theories discussed in the literature section; however it goes one step further by combining the substitution methods for which a two-way substitution method is proposed.

The first step of this method focuses on utilization of the C component variants kept in stock, in order to increase their utilization and free up the stock capacity. C components have by definition lower sales volume. They are taking up more space in the stock and for a longer time period, than the A components, which are used frequently. Moreover the average lot size of the C products is small, which is related to increased changeover and set up times, implying for increased cost and complexity in the production flow. The quantification of the stock capacity is calculated based on the average number of pallets occupied by each component in stock. The machine utilization is calculated on the number of components produced per run.

According to the suggested method, the C components kept in stock would replace the similar components in the A products. The main challenge is to identify which C variants could substitute the A variants in the final product assembly, without compromising neither the quality nor the specifications of the finished product. This first method can be seen a short-term suggestion, with a focus on achieving immediate impact in production

The second step of the substitution method proposes a long-term solution, in which the A components substitute the C components in the final product. This results in out phasing the C components of limited utilization, which leads to an increase of the stock capacity. At the same time the replacement of C components enables higher production and stock utilization of the A components, as manufacturers can plan with higher lot sizes. This action results in optimizing the machinery utilization, especially for those machines that are potentially creating bottlenecks. The optimization is succeeded by reducing the change overs and the setup times for producing A components. In relation to the stock capacity, the substitution of the C components has positive effects, as the slow moving pallets with C components are replaced by pallets with A components.

This step of the suggested approach identifies the relations between the substitution and changes in the lot size, and their impact on the production process.

4.3.1.1.3 Lot size and capacity utilization

The third step of the suggested approach, builds upon the previous and examines the relation between lot size and machine utilization. The reviewed theories indicate a connection between the lot size and the optimization of output of each machine in the production process. The bottleneck machines are of great importance in this stage. Additionally, the lot sizing is related to the second step of the substitution method (A components used for C variants). As the total volume of the A components increases, the manufacturer can plan with a higher average lot size of the process flow.

4.3.2 Operational method for managing product variety

Based on the literature review in chapter 3, an operational method for developing a strategy for product assortment in CTO companies is developed. The suggested framework builds upon the related research fields and attempts to include all aspects that should be taken into consideration in order to develop a strategy for managing product variety.

It consists of four main phases, which have been suggested by product planning literature. The first step is scoping and defining the focus of the products to include in the analysis. The second step is an internal analysis, which is mainly inspired by literature on profitability analysis (Hansen et al. 2012, Wilson & Perumal, 2009). The third step is an external analysis, as suggested from the product planning literature. The core idea suggests an analysis of competitors' and their products in order to place the company under investigation in its market position. The final step is a synthesis. Based on the results from the internal and external analysis, suggestions are made for future development. The four steps of the operational method are briefly presented in the following figure and further described in the following sections.

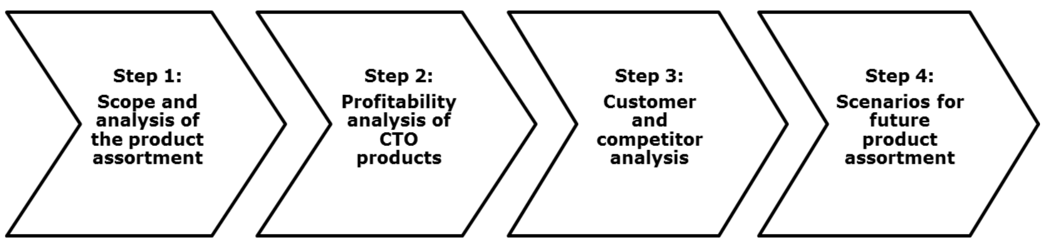


Figure 4-4 Operational method for managing product variety

4.3.2.1 Scope and analysis of the product assortment

The suggested operational method has as its starting point the definition of scoping within a project. Firstly, it has to be clarified which products and/or product families are to be included in the analysis. Based on experience and the literature review on case studies within this area, the main indications for a product to be included in the analysis are low profitability and a decrease in sales volume. These two factors usually signal a need for action and further examination.

Additionally, since the focus is on CTO products, an overview of the technical characteristics of the products is performed. This overview enables better understanding of the product range in terms of structures, components, dimensions, applications, sales price, cost prices etc. The Product Variant Master (PVM) technique is used at this stage to analyze the product structure, including component features, assemblies, and main attributes (Hvam et al. 2008, Nielsen et al. 2010). An in-depth PVM model gathers almost all data required for the following steps of the discussed framework. Data for this step are to be collected from the designs of the products and the company's internal database, such as Product Lifecycle Management (PLM) (Zhang & Tseng, 2007) and Enterprise Resource Planning (ERP). Un- and semi- structured interviews with persons involved in each project are performed to supplement the accuracy of the findings.

4.3.2.2 Profitability analysis of CTO products

Once the analysis of product assortment is performed, the next step refers to the analysis of profitability. Data collection includes sales numbers, cost price, and sales price, which are provided by the company's database (De Reyck et al., 2005). Regarding cost price, it is of great importance to ensure how it is calculated. The most common approach describes that cost price includes material cost and production cost. Additional factors that might add up to the production cost are, as identified from the existing literature, engineering, labor, machinery and inventory costs (Zhang & Tseng, 2007).

Furthermore, an aspect that has to be taken into consideration while performing a product profitability analysis is whether the product is sold as an individual unit or as a sub-assembly. Spare parts are also to be examined separately.

The next task of the second step is to calculate the contribution margins of product assortment. Contribution margin is calculated as follows, sales price minus production cost (Farris et al., 2010). As mentioned above and for this case study, production cost includes material and direct labor costs. In some cases it is relevant to include indirect production costs, which could be tools, machines, the rent of a warehouse, and white-collar wages.

Then, a contribution ratio (CR) is calculated as the percentage of the contribution margin of revenue. This calculation has to be made on a product- and on a product family- level. The results from this analysis reveal dependencies among the different aspects of the product assortment, indicate the most profitable products, and separate those that contribute on a lower level to the benefits.

4.3.2.3 Market, customer and competitor analysis

Step 3 is the analysis of the market, focusing on customers and competitors, in order to understand the placement of products in the market. To perform the customer analysis, information can be gathered on several levels, such as on the level of specific companies, industrial sectors or countries. Data related to customers include sales number, discount policies, and the exact variants that each customer purchases. The last variable is used to define the possible linked revenue of each product. The outcome of this analysis is the classification of the customers and the identification of the interdependencies among the customers and the product assortment (Lehmann & Winer 2005, Flapper et al. 2010).

The second phase of step 3 continues with the analysis of competitors (Haines, 2009). At first, the competing companies have to be identified, and the products they are offering have to be described in a similar way as for the under examination products. This enables a comparison on valid terms. The PVM technique is also suggested at this phase for competitive products. The required level of detail is not as high as it is for the analysis of a company's own products. This is because the prior interest at this point is to make a comparison among the characteristics that have been identified as main "strengths" and/or "weaknesses" of the own product assortment and of the competitive products. It is realized that due to confidentiality and competitive issues, it is not possible to gather the same amount of information for competitive products. Sales prices and technical characteristics that can be obtained from sales catalogues are of main interest.

An overall conclusion can be drawn by calculating the relative market share for the competitors and the company.

4.3.2.4 Scenarios for future product assortment

The final step of the suggested operational method refers to the development of scenarios for a future optimized product assortment (Millett 2003, Schoemaker 1995). Scenario creation is based upon the outcomes and conclusions of the previous three steps of the analysis.

The scenarios may vary from case to case; however, they are developed based on two main concepts as identified from the literature review; variety reduction and changes in production flow. Please list here the three concepts.

The first scenario refers to decreasing the number of variants (Suzue & Kohdate, 1990). One way that this solution can be implemented is by eliminating the less profitable variants, which have been identified from the second step in the analysis of the profitability of the product assortment (Jiao et al., 2007); linked revenue and product substitution have to be taken into consideration in the analysis of this scenario. Moreover, the re-designing of specific components, or even products, is another option, which decreases product complexity and manages to maintain the existing variety offered to customers. Re-engineering costs have to be calculated, and the effect of the redesigned products, in terms of materials, dimensions and production process has to be measured based on related aspects, such as freight, inventory and production costs.

Another way of implementing this concept is by complete elimination of the product assortment. This scenario is considered as a drastic solution as it suggests a complete stop of production, in cases where the previous two scenarios do not offer enough benefits to invert the situation of poor performing products. Substitution of obsolete products and linked revenue has to be scrutinized.

The second scenario includes changes in the production flow. Investment in new machinery or new production sequences are the most common suggestions (Ramdas 2003, De Groote 1994). All the related costs have to be estimated, as well as the depreciation period of any investment.

The final step is completed by an evaluation of the suggested scenarios and the final decision is taken after the comparison of the assessed scenarios that point out the most suitable solution for the development of the future strategy for product assortment.

The suggested operational method discussed in this section is applied to a case study. The description of the case and the results are further discussed in the following section.

4.4 Main findings from the case studies

The suggested frameworks address the issue of analysing the profitability of the product assortment, on different levels. The analysis of profitability is discussed on component and final variant level. The second approach expands the limits by examining not only the profitability of the product portfolio, but the market and competitor analysis as well. Both methods are concerned with concepts to be used in order to develop initiatives for control and reduction of product and process complexity. This is interpreted in terms of cost reduction, profitability increase, reduction of number of final variants, product substitution and improvements in the production flow and inventory management.

The suggested methods are developed based on the analysis and synthesis of existing theoretical concepts, as discussed in chapter three. Yet, the scoping of their application is quite broad. This is beneficial for the research project as the applicability of the suggested methods can be tested on different cases studies, in order to provide validation and generalizability.

Nevertheless, this wide range of application areas could be considered as a challenge of the research. One could argue that there is a need to limit the scope of the application of the suggested methods. The main argument for that is to allow replication of the study. By narrowing down the focus of the methods, more explicit criteria can be defined regarding the requirements that a company has to fulfill in order to use the suggested methods and achieve optimum results.

To this end, the issue of data acquisition has to be addressed as a challenge. It has been realized that data collection is possible to vary among the different companies, based on the availability of the data in each case. It is not always possible to collect exactly the same data or for the same time period. This limitation is further discussed previously in section

2.4. By limiting the scope of the application of the suggested methods and introducing more specific criteria for the case companies, this challenge can be overcome.

In relation to the DRM framework, the following table presents the main findings from the case studies in relation to the stages of DRM, RQs and case companies used.

Table 4-2 Findings from the CS in relation to DRM and RQs

	Research Clarification	Descriptive study I	Prescriptive study	Descriptive study II
RQ I				I II III IV V VI VII
RQ II		VIII XII		VIII
RQ III		X XI		I II III IV V VI VII X XII XII

5 RESULTS

5.1 Findings from the studies

During this PhD project six main studies were performed in order to develop and test the related methods and tools for management of complexity. The following sections discuss and evaluate the outcome of the six studies. The studies are conducted as follows:

Study 1: Complexity Cost Factors
Study 2: Managing complexity of product mix and production flow
Study 3: Operational method for managing product variety
Study 4: Reconfiguring variety, profitability and postponement for product customization with global supply chains
Study 5: Impact of product configuration systems on product profitability and costing accuracy
Study 6: Impact of the utilization of a product configuration system on product's life cycle complexity

5.2 Complexity Cost Factors

5.2.1 Introduction

The first part of the research focuses on the identification of CCFs. For that purpose 7 companies are used as case studies. The study is part of Papers A and G. The results are discussed in the following section and contribute to answering RQ I and RQ III.

5.2.2 Results for CCF identification

In order to identify the factors responsible for complexity costs, the following proposition has been formulated and tested in the case studies:

Proposition 1. Which CCFs identified from the literature may be used to identify and quantify complexity costs in a manufacturing company?

In order to test the factors identified and provide empirical evidence, the complexity costs have been analyzed in seven manufacturing companies by applying the relevant factors. The following table provides an overview of the CCFs identified in each case. After each CCF, if identified in a case, the ID of the company follows (e.g. I, II, III etc.). When quantified, the ID of the company appears in bold.

Table 5-1 Categorization of CCFs in the case-studies under the APQC standard

Product/ Process	CCF	No of components	No of FG
Plan for and align supply chain resources	Material flow pattern	-	IV
Procure materials and services	No of suppliers	**VII**	**VII**
	Cost of sourced components	**-**	**III**, IV
Produce/ Manufacture/ Deliver product	Operator	V	V
	Capacity utilization	**VI**	**VI**
	Set up	IV	**-**
	Changeover	V, **VI**	**-**
	Batch size	**V, VI, VII**	**-**
	Capital costs (rent/heating)	VII	IV, V, VII
	No of production lines	-	IV
	Manufacturing strategy	-	IV
	Resources	-	IV, V
Manage logistics and warehousing	Transportation and handling within the production site and warehouse	**II,** VII	**I,** IV, **V,** VII
	Product assortment in inventory	**I, II, III, IV, VI, VII**	**I,** II, **III, IV, V, VI, VII**
	Scrap	VII	I, **V,** VII

	Location of warehouses	IV	**-**
	Administrative costs	**-**	I, **IV**
	Freight	**-**	**I, IV**
	Insurance	**-**	**V**
	Shelf-life	**-**	VII
Markets, customers, and capabilities	No of orders	**I**	**I**
	Order size	**I**	**I**
	Demand/Sales	**-**	**I**
	Order taking process	**-**	II, **IV, VII**

As it can be seen from the table above, CCFs identified in the case-studies cover the same business processes as from the literature review. The main limitation to this research is the availability and validation of the data acquired. For that reason, the research team was not able to quantify all the CCFs identified. The most frequent CCFs identified and quantified, both from the literature review and the empirical evidence, are the product assortment that is kept in stock and the transportation and handling within the production site and warehouse. Nevertheless, there is no pattern identified regarding which CCFs are found in each case and if they are connected.

After identifying the CCFs and quantifying complexity costs, several initiatives have been developed and evaluated for each of the cases regarding complexity reduction and control. Since the identified factors are different for each case, the scenarios developed vary but are developed based on two main concepts: product complexity (e.g. reduction of variants Suzue and Kohdate [1990], Jiao et al. [2007]) and process complexity (e.g. optimization of the production process Ramdas [2009], De Groote [1994]).

In detail, reduction of product complexity is a suggestion applied to all the case companies. This scenario is implemented through a number of different initiatives such as reduction of product range, elimination of variants, standardization of the portfolio, reusability in product design and substitution on both finished good and component level. Regarding process complexity, the initiatives implemented to the case companies are process optimization, distribution of products and inventory management.

The following table (Table 5-2) illustrates the results from the identification and quantification of the CCFs in the case studies, the scenarios suggested for reducing and controlling complexity and their impact. In the last column, the impact of the suggested actions to reduce complexity is quantified. Based on the availability of the data acquired in each case study, the impact is measured as Earnings before interest, taxes, depreciation and amortization (EBITDA), CM, calculated as the difference of the NR minus the direct cost (Farris et al. 2010), CR, calculated as the percentage of the CM divided by the net revenue. In order to allow comparison among the different case companies the unit of the impact is in million Euro (m€).

Table 5-2 - Complexity management in case studies

Company, Product, No of variants	Factors quantified	Actions	Impact
I **Medical devices, sensor cassettes** 120	○ Transportation and handling within the production site and warehouse ○ Product assortment in inventory ○ No of orders ○ Order size	○ Adjusted portfolio based on different properties of the product lines, not the individual products, reduction by 28% of the products offered ○ Process optimization, capacity improvements and shift model, new factory	○ Discontinuing 35 variants increases EBITDA to 27,2 m€ ○ New capacity strategy increases EBITDA by 25,1 m€ in 6 years (current 165 m€)
II **Pumps** 2736	○ Transportation and handling within the production site and warehouse ○ Product assortment in inventory	○ Reduction of the product range ○ Standardization of the portfolio	○ 4,3% cost reduction and 18% CM increase by merging 36 products (12% of portfolio)
III **Analytical instruments** 40	○ Cost of sourced components ○ Product assortment in inventory	○ Product portfolio management ○ Increase standardization and reusability in product design ○ Inventory costs reduction	○ 24% reduction in material cost (1,8 m€) ○ 30% reduction in inventory cost (0,32 m€)

IV **Commercial electrical appliances** 350	○ Product assortment in inventory ○ Administrative costs ○ Freight ○ Order taking process	○ Elimination of C items – No substitution ○ Elimination of C items – 100% substitution ○ Elimination of C & B items – No substitution ○ Elimination of C & B items – 100% substitution	○ Scenario 1: 2,1% CR increase ○ Scenario 2: 1,3% CR increase ○ Scenario 3: 1,9% CR increase ○ Scenario 4: 1,2% CR increase
V **General Building Insulation products** 175	○ Batch size ○ Transportation and handling within the production site and warehouse ○ Product assortment in inventory ○ Scrap	○ Decrease product assortment ○ Increase substitutability	○ Total savings after both scenarios 20-25 m€ (8-11%) of EBITDA 236 m€
VI **Mattresses** 3714	○ Capacity utilization ○ Changeover ○ Batch size ○ Product assortment in inventory	○ Product substitution (scenario 1 & 2) ○ Process optimization (scenario 3)	○ Warehouse capacity optimization by 11,3% ○ Component reduction by 31,4% ○ Savings from process optimization 0,25 m€

VII **Frozen food** 666	○ No of suppliers ○ Batch size ○ Product assortment in inventory ○ Order taking process	○ Decrease product range ○ Decrease no. of suppliers ○ Inventory management	○ Remove 15% of the products , which are unprofitable, and increase EBIT by 0,05 m€ ○ Savings by product substitution 0,2 m€ ○ Increase profit 0,09 m€

In each of the under examination case studies, the scenarios for complexity elimination are related to the factors identified. For example, in the case of company III the CCFs identified are cost of sourced components and product assortment in inventory. Based on these, the suggested initiatives include standardization in product design in order to increase reusability of components and parts used in the finished products. The second initiative addresses the cost of keeping both components and finished goods in stock and it suggests keeping in stock products and components used in products that are high sellers, since they spent less time in the warehouses, they do not become outdated or obsolete and this leads to decreasing the cost of inventory.

As mentioned above, one of the most frequent CCFs identified and quantified both in the literature study and in the case studies, is the product assortment in the inventory. In the case companies that this CCF is identified the suggested actions include component and product substitution as an immediate action to reduce product and process complexity. For the products that are producing no profit, complete elimination is also one of the actions taken (Wilson & Perumal 2009). Additionally, the standardization of the product platforms is suggested as a long-term measure in order to increase reusability of parts and components in the finished products. Reducing the product complexity leads to reduction in process complexity. By looking into the same example of the CCF of the product assortment in inventory, we can see from the case studies that the reduction in the number of parts or finished goods that are kept in stock has a direct effect on capacity optimization of the storage space, the production lines and the overall cost.

Regarding the impact from each of the suggested actions in the case-studies in order to tackle product and process complexity, there is a variation, as it can be seen in the last column of Table 5-2. Another issue that is identified by comparing the impact in the different case-studies is the fact that due to data availability and verification in each company, the impact is quantified using different methods and indexes. For instance, in company I and V the impact is quantified by using the EBITDA, while in company IV is presented as a percentage of the CR. At last, another lesson learnt from the case studies is that even companies with relatively smaller product assortment can also benefit from reducing underlying complexity costs. For example, by comparing the results from the companies II and III in Table 5-2 we can see that company III has 40 product variants while company II 2736 product variants, yet product complexity is still identified and by implementing initiatives to control and reduce complexity the impact is worth mentioning.

5.2.3 Conclusions

This study applies the results of the literature research on CCFs to multiple case studies. The list of factors identified in the literature is used as a checklist in the case companies. Furthermore, initiatives for controlling and reducing complexity are developed in terms of variant elimination and product portfolio standardization. The preliminary results of this research, focusing on the identification of the CCFs, are presented in the Paper A and they used to provide an answer RQ I. The detailed results, including the testing of the developed initiatives for complexity reduction, are included in Paper G and contribute to answering RQ III.

5.3 Managing complexity of product mix and production flow

5.3.1 Introduction

The focus of this study is to test the proposed framework and quantify the production flow optimization by adapting the product assortment. The suggested framework is discussed previously (section 4.3.1) and consists of three main steps. The first one is the ABC product categorization, then variant substitution to improve the process flow and finally, optimization of the relationship between lot size and capacity utilization of bottleneck machinery. Case study VIII is conducted for this part of the research project. As explained before, the challenging aspect of this specific case study is the lack of expanding options, especially on large scale such as expansion of the production site or the warehouse, purchase of supplementary machinery. There is limited available space in the production facility, which corresponds to a small machine or a new stock point for products in small volume. As a result the chosen case study is selected as an example where the optimization of production flow and capacity utilization could only be achieved by the following proposition.

Proposition 1 (P1)

Substitution on a module and component level contributes to improving of the production flow and capacity utilization of machinery and inventory.

This study is presented in Paper B – Managing complexity in product mix and production flow.

5.3.2 Complexity analysis at the current state

In order to implement and evaluate the suggested approach on this case study, the analysis of the current state is to be used as a baseline. The following figure illustrates the current production flow, with the bottleneck machines and stocks marked with grey.

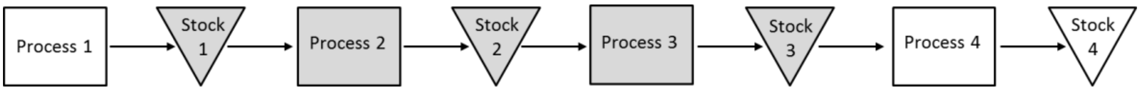


Figure 5-1 Current production flow with bottlenecks

With reference to the production process, the products go through four machines. There are also four stock points, after each process. Based on the analysis of the data acquired, the production process was analyzed and the bottleneck machines were identified. The utilization ratio of each machine is used for that purpose, and is calculated by the following formula.

Equation 5-1:

$$r_u = \frac{T_{projected}}{T_{theoretical\ available}}$$

The projected time refers to actual time that the machine was in use and is calculated as the sum of the queue time, set up time and process time. The theoretical available time is the total time for the shifts that are allocated for that specific machine. According to the production plan, each machine is running in three shifts per day. The utilization ratio is the percentage that enables to identify the machines that create the bottleneck in the production flow.

Based on the results all the intermediate stock points are exceeding the available capacity (see Figure 5-1, stock 1, 2 and 3), with utilization rate close to 100%, and in some cases up to 117%. The two machines operating the processes among these stock points (see Figure 5-1, process 2 and 3) have also utilization rate that exceeds 100% in 10 days out of 21 working days in the month the data refers to. As the focus of this study is to improve the production flow by optimizing the product mix and machine utilization, the next step is to analyze the products.

Implementing the suggested approach, an ABC analysis was performed to the finished products, and subsequently to the components. The following figure illustrates the relation between the volume of the finished products and the number of variants, based on the ABC product differentiation made after the related data was acquired. The data used for this ABC categorization is the net revenue from each and every product.

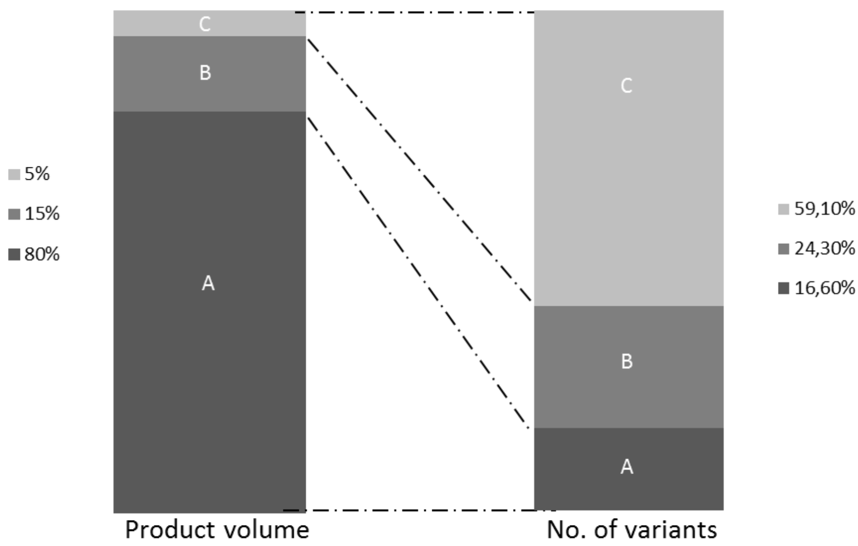


Figure 5-2 Percentage of net revenue and number of product variants

Similarly, by relating the number of products to the contribution margin the result demonstrates that 80% of the contribution margin is generated by 16,4% of the products, which are categorized as A. the C products that create 5% of the contribution margin correspond to 59,1% of the product portfolio.

The results from the ABC categorization are presented in the following table. In order to categorize the products and the components as A, B or C the net revenue and the contribution margin were used. By applying the double Pareto law, the outcome of this grouping shows that only 17,4% of the products are generating high revenue, while the majority (60,9%) create the long tail (Wilson & Perumal, 2009) .

Table 5-3 ABC product categorization

Product category	Net revenue [m€]	Contribution margin [m€]	No. of products	% of products
A	111,8	65	386	17,4 %
B	18,4	10,9	481	21,7 %
C	7,6	4,5	1351	60,9 %
Sum	**137,8**	**80,4**	**2218**	

The analysis of the current state constitutes the first step of the proposed framework. The historical data on sales volumes helps to estimate the current market trend and indicates in which steps of the production the capacity exceeds the maximum level, both in machinery and stock keeping units. The current state is used as a baseline scenario and serves when evaluating the alternative solutions.

In order to analyze the intermediate stock points, the following figure shows the average time for the A, B, and C components kept in stock. C components have in average 20 times more inventory time than A components. Due to this ratio, by eliminating C components the stock capacity will increase rapidly.

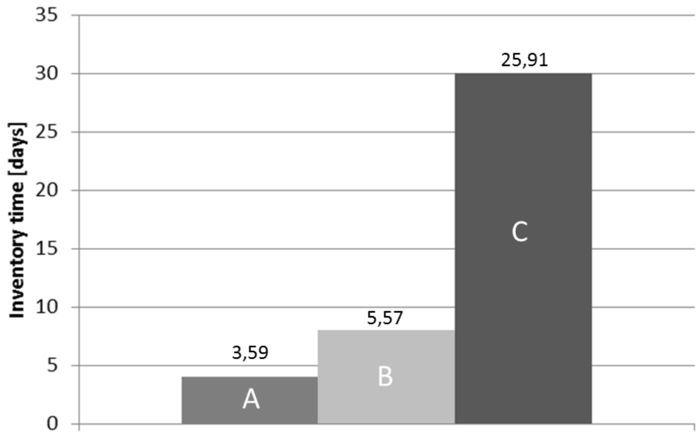


Figure 5-3Duration of components spent in stock per ABC component group

Additionally, based on the number of pallets in stock for each component, the following figure clearly illustrates that C components require higher capacity, due to the fact that they are slowly moving. C components take overall 43% of the available storage space.

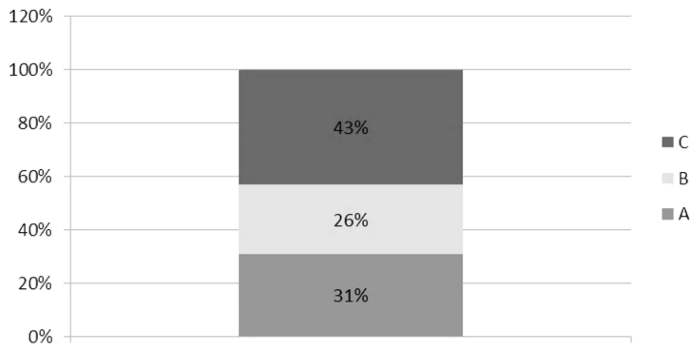


Figure 5-4 Percentage of stock capacity occupied per ABC component group

With reference to the machines that also create bottleneck in the production process (see Figure 5-1, process 2 and 3), the following figures illustrate the production time lost due to changeovers in each machine. However the average utilization ratio of machine 1 is 82% and of machine 2 is 87%. This indicates that the machines' capabilities are not utilized to their maximum capacity, even though the production might be behind schedule, while some days they exceed their utilization ratio in order to keep up with the demand. This is due to the fact that the intermediate stocks have reached their maximum capacity limits; as a result they cannot accommodate the additional production volume.

In order to analyze further the machines in process steps 2 and 3 that create bottleneck, the changeover time is measured. The following two figures, Figure 5-5 and Figure 5-6, illustrate the average changeover time that is spent in every run for machines 2 and 3 respectively. The figures demonstrate the comparison among the time required for the different variants, A, B and C. It can be seen from the figures that the average times for B and C variants do not differ significantly from the average times of the A variants, even though the B and C variants combined correspond to 20% of the total net revenue. In detail, regarding the second process of the production flow (see Figure 5-5), the average total time that the machine is running is 6,2 hours. By combining the average time that is spent at changeovers for the B and C variants, it can be calculated that the 37 minutes required for the changeovers correspond to 10% of the total production capacity.

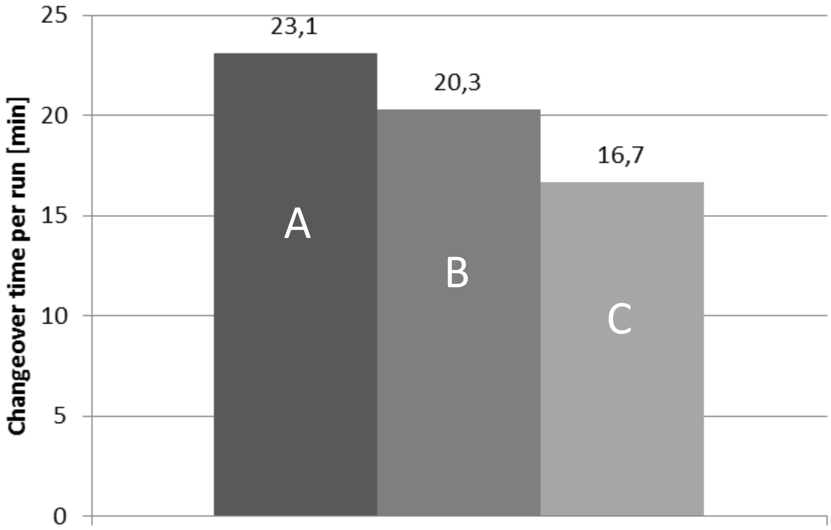


Figure 5-5 Average changeover time per run per ABC variant group for process 2

Similarly for the third process (see Figure 5-6) the average changeover time for B and C variants combined is 35 minutes, corresponding to 9% of the production capacity for machine 3. This means that the B and C components, which are not the most profitable components that are produced, occupy the machine for 35 minutes to perform the changeover, while the A components have lower average changeover time for each run (12,1 minutes). The delays due to the changeover time contribute to the creation of the bottleneck in the process steps 2 and 3.

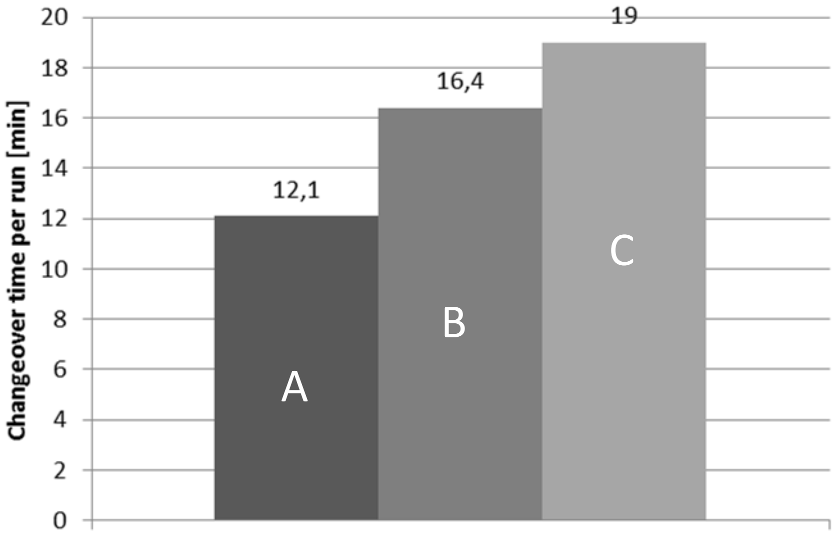


Figure 5-6 Average changeover time per run per ABC variant group for process 3

5.3.3 Suggested initiatives to reduce complexity

5.3.3.1 Scenario 1

The first scenario suggests substituting C variants with A variants on component level, i.e. at an early stage of the production process. In our case study, the results from the early component variant decrease through substitution lead to a reduction both in stock capacity requirements, as well as in the bottleneck machines. This suggested solution has a direct impact on the first stock, by reducing the number of C products occupying capacity. By substituting the C components with A, the storage space will become available for A components, which will also lead to increase the production of A components.

5.3.3.2 Scenario 2

The second scenario consists of a combined short and long term solution, with two-way substitution at a later stage in the production process. The first step suggests the substitution of A variants by C variants, in order to reduce the number of the slow moving C variants in stock. This approach could be applied due to fact that the substitution will not jeopardize the quality of the final assembly, as for the case products the only difference between the two variants is the size of components (length, width). As a result the variation of the final products would not be affected. The effect of this solution can be realized in the released capacity of the second stock.

The second step of this scenario is the long term suggestion, which introduces substitution of C components on the final products by A. The substitution takes place at a later stage of the final assembly. The outcome of this scenario is a great reduction of stock capacity requirements, as the slow moving C variants are no longer produced. This strategy results in freeing up the space occupied by C variants and providing more space for the widely used A variants. The following figure (Figure 5-7) illustrates the expected results from implementing the suggested approach. The current state is compared to the future state with and without implementing the recommendations.

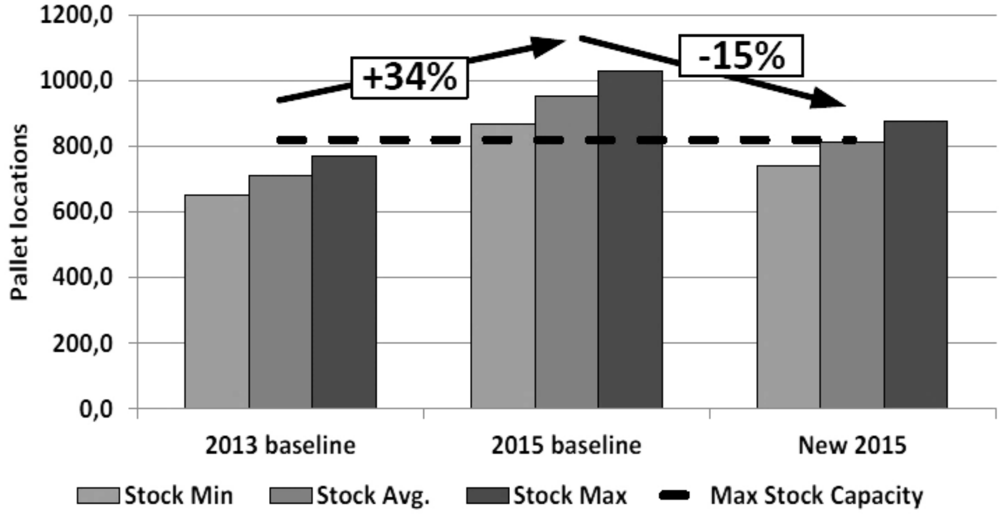


Figure 5-7 Capacity utilization improvement of the second stock

Furthermore, this solution targets the bottleneck machines. By eliminating the production of C components and replacing it with A components, changeovers are decreased and, subsequently, production time lost due to many changeovers can be used to improve machine utilization.

However, by substituting C components by A leads to an increased waste of material. The A components have bigger sizes than the C, so in order to apply the substitution approach, additional material has to be cut. This leads to extra scrap of approximately 2.680 Euro per year. This scrap is calculated by comparing the dimensions of the A components to these of the C components that are subjected to substitution. Taking into account this additional cost, the following table demonstrates the cost calculations for the implementation of the two-way substitution. The results of the aggregated approach reveal that regardless the extra scrap cost , the capacity optimization is improved by 11,3% free-up pallets and 31,4 % reduction of components is achieved.

Table 5-4 Summary of substitution strategies

	C components for A product	A component for C product	Both strategies
Total no. of variants	618,8	618,8	618,8
Total no. of eligible C components	137,8	24,7	149,5
Total variants %	28,9 %	5,2 %	31,4 %
Total no. of pallets	83,93	14,97	92,70
Total pallets %	10,2 %	1,8%	11,3 %
Cost per pallet [€]	2.982,82	15.796,66	5.252,86
Total cost [€]	192.649,05	181.933,90	374.582,95

5.3.3.3 Scenario 3

The third scenario suggested builds upon the previous step of component reduction and increased storage capacity. In order to improve further the machine utilization, separation of the production and storage of the A and C components is suggested. Based on theory the output per run of a machine is increased as the batch size increases. This indicates that the production flow is to benefit from separating the production of C and A components by introducing a new machine that is devoted to the production of the C components and a separate stock before that. In that case, machine utilization will be improved for the high-run A components. For that purpose, the suggested approach includes the purchase of a new machine and the creation of a new stock, in order to allow the distinction of the production and stock of A and C components.

With reference to the machine utilization, the following figure illustrates the relation between the average lot size and the number of components produced per run. The tendency is quantified to the following formula.

Equation 5-2:

$$y=5,0433x+123,36,$$

where y corresponds to the number of components produced per run and x to the average batch size.

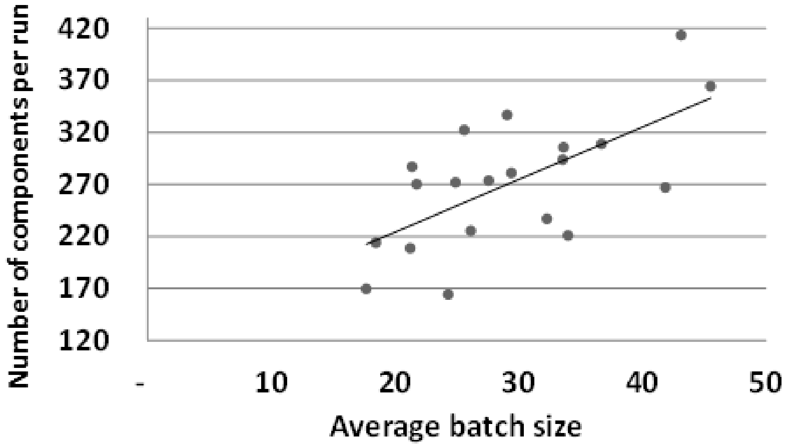


Figure 5-8 Relation of lot size and production

The figure above (Figure 5-8) indicates how the machine utilization benefits from the increasing lot size for the specific production set up. The number of components produced per run is directly depended on the lot size. This implies that for the A components, where the production is high, the optimum lot size should be increased. By taking into account the changeover and set up time for the production of A and C components, the third scenario targets both on reducing the bottleneck forth machine and improving the capacity of the third stock. By applying the third scenario the realized benefits regarding the stock capacity optimization are illustrated in the following figure. The results indicate that by storing only A components 46% freed stock capacity can be achieved compared to the forecasted capacity requirements without implementing any changes to the current state.

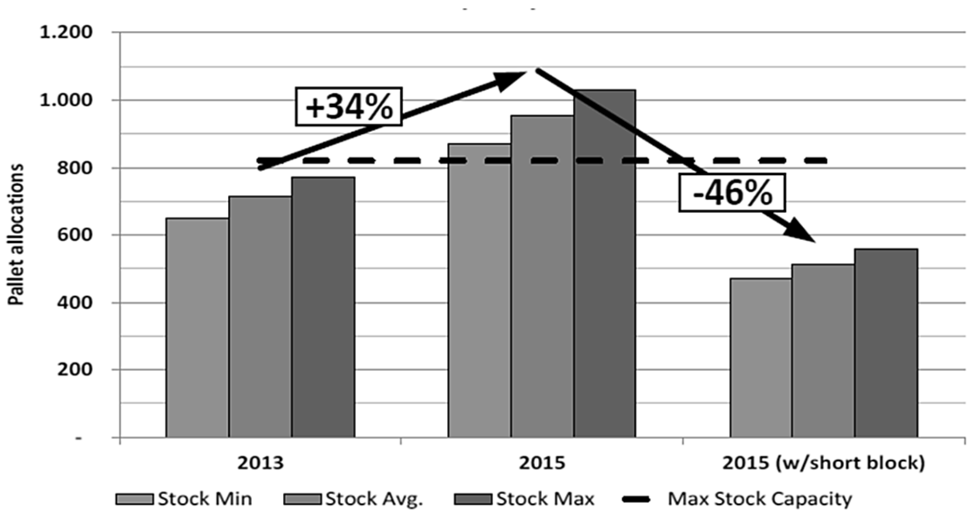


Figure 5-9 Expected capacity improvement of third stock

5.3.4 Discussion

The results from the case study reveal that there is a relationship among the two-way component substitution and optimization of the process flow. All three suggested scenarios indicate that the reduction in the production of C components has a direct impact on the optimization of the stock capacity and elimination of the bottleneck machines. By combining the scenarios step wise, the final expected outcome for a two year period demonstrates that there is a significant improvement in the use of the stock capacity. The figures 5-7 and 5-9 illustrate the capacity utilization for the components kept in the second and third stock by comparing three states the current situation, the future state (in two years) without making any changes and the future state after implementing the suggested approach. The result shows that by substituting the C components with A, the average stock capacity will not exceed the maximum limits.

With reference to the cost of the suggested approaches, one cost aspect that should be taken into consideration is the extra scrap due to the size difference when evaluating the substitution of C components by A. On top of that, another cost is related to the purchase of the new machine required in the third scenario, for creating a separate production process for the C components. In order to evaluate the feasibility of that solution the cost of the shifts (standard and extra) and the cost of the new machine are calculated. The following tables (Table 5-5 and Table 5-6) demonstrate that the extra cost of the new process line is approximately 101.250 Euro, while the annual savings due to the elimination of the extra shifts due to the optimized process flow is approximately 254.250 Euro.

Table 5-5 Annual extra cost for the new process line

	Weekday			**Weekend**		
	Night	Day	Evening	Night	Day	Evening
Hourly salary [€]	33	27	31	39	35	37
Hours per shift	7,5	7,5	7,5	7,5	7,5	7,5
Operators per shift	2	2	2	2	2	2
Extra shifts required	0	5	0	0	0	0
Weekly extra cost [€]	-	2.025	-	-	-	-
Annual extra cost [€]	-	101.250	-	-	-	-
Total annual extra cost [€]				**101.250**		

Table 5-6 Annual savings from reduction of extra shifts

	Weekday			Weekend		
	Night	Day	Evening	Night	Day	Evening
Hourly salary [€]	33	27	31	39	35	37
Hours per shift	7,5	7,5	7,5	7,5	7,5	7,5
Operators per shift	2	2	2	2	2	2
Extra shifts required	0	0	0	- 4	-1	-4
Weekly extra cost [€]	-	-	-	-2.340	-525	-2.220
Annual extra cost [€]	-	-	-	-117.000	-26.250	-111.000
Total annual savings [€]				**254.250**		

5.3.5 Conclusions

This study presents the results from testing the suggested framework in terms of managing product and process complexity, and their interrelation. The results from the case company indicate that even with the specific restrictions of the layout, noteworthy savings can be achieved by reducing complexity in products and processes. The preliminary study is presented in Paper B and the detailed study in Paper H. The results from this study contribute to answering RQ II.

5.4 Operational method for managing product variety

5.4.1 Introduction

This study focuses on developing and testing an operational method for managing variety in a manufacturing company. The method, discussed previously in detail (section 4.3.2), consists of four steps: analysis of the product assortment, profitability analysis, market analysis and scenarios for future product assortment. The empirical results of this study are presented in the following sections. For the case study, company IX in the heating and ventilation industry is chosen. In recent years, the company has been facing a decreasing number of sales in the main product family of its portfolio along with declining revenue.

This study is presented in Paper C and contributes to answering RQ III regarding control and reduction of complexity.

5.4.2 Analysis of product assortment

In the company, the profitability of several groups of products has been discussed for years. In order to focus on and delimit the analysis work, only one of these product groups has been selected. The criteria for selecting this specific group of products is that the overall profitability seems very low and the amount of products in the scope can be analyzed with a reasonable use of resources. Finally for these products, the company had the data needed for the analysis.

In order to define the scope of this analysis, the research team, along with the managers of the company, first has to consider which products, out of the whole portfolio require further investigation. The examined product family has been characterized by a declining number of sales for the last several years. At this point, the company is considering its options in terms of whether there is profit in maintaining the production or whether discarding the whole family from the product portfolio is a more viable solution.

The product family consists of three products, A, B and C. Product A has the largest size of all, and it is the second most beneficial in terms of net revenue. The market for A is mainly the food industry. Product B contributes the most to NR, it has the smallest size and its market is within the industrial sector. Product C is the newest addition to the product portfolio of the company. It has a medium size and low contribution to NR. Due to the difference in the material of product C in comparison to A and B, the marine sector is its main market.

Table 5-7 Product assortment

Product	***Size***	***Revenue***	***Market***
A	Large	Medium	Food industry
B	Small	High	Industrial sector
C	Medium	Low (new product)	Marine sector

The PVM technique is used to a gain technical overview of the product structures and their components.

5.4.3 Profitability analysis of configured products

The first step in the analysis of the profitability of the three products is the annual sales numbers. Data are acquired from the ERP system of the company referring to the last six years. 4.434 orders have been placed for the product family, which resulted in 7.090 units sold. In details, for product A 714 units have been sold and for B 4.912 and for C 1.464.

From the following sales figures, variants that are used as parts of other solutions are excluded; this is due to the fact that the sales price is not registered for each part used but only for the final solution.

The variants taken into account had to meet three criteria: every order has to have an active expected cost price, actual cost price and sales price, in order to have coherency among the data analyzed.

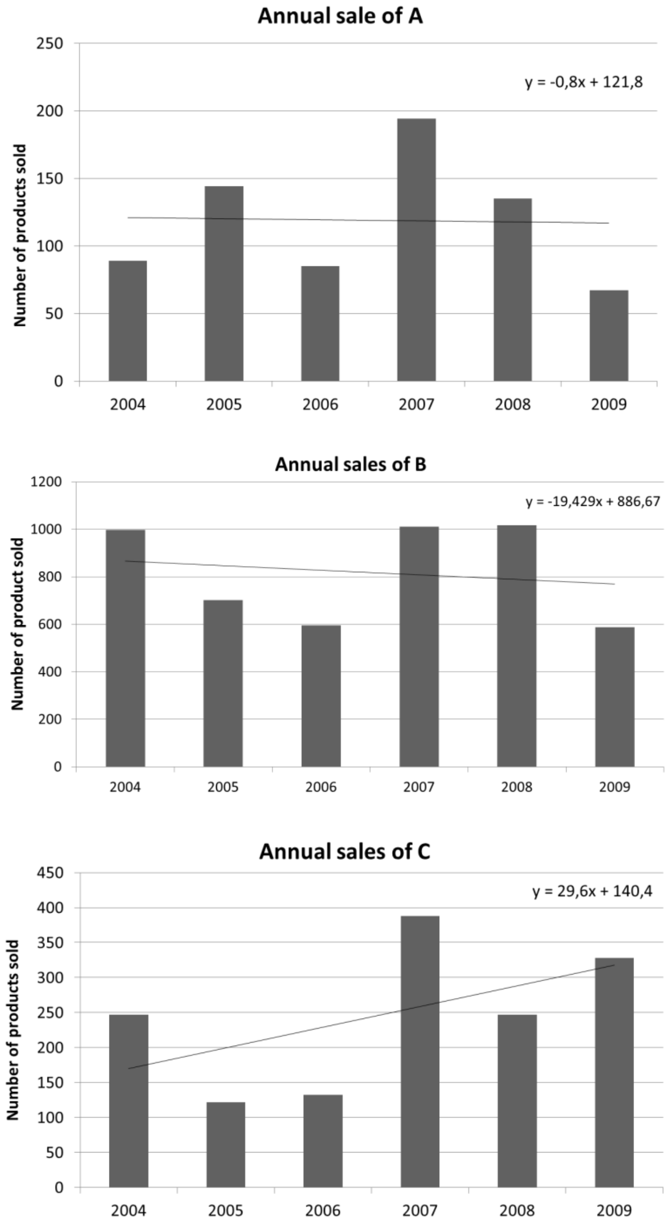


Figure 5-10 Annual sales of products A,B,C

Data provided by the company include:

- the transaction dates of sales provided in the format month/year, project number
- sale price
- number of units sold
- actual cost
- expected cost
- description of sales
- sale type, indicating if the transaction is a single piece sale or part of other solutions
- country where the sale is carried out.

Spare parts are also excluded from the analysis as there is lack of information about their exact size and the sales country. An analysis is made for each product. The difference between the sale price and the cost price provides the basic contribution margin.

The expected cost price originates from the company's product configurator and is based on bills of material calculation and the cost of labor in the production. The actual cost price comes from the post-calculation at the end of production and includes the same parameters that are used in the previous calculation. The ratio between these two figures gives an indication of whether the configurator is miscalculating a given order or whether there has been some kind of problem in the production.

By performing a Grubb test for the outliers, it is concluded that orders within the range of 65 % and 135 % of the expected cost price are acceptable. The Grubb test detects the outliers and then it expunges them from the dataset. This allows a valid statistical analysis (ISO 5725-2, 1994).

5.4.3.1 Contribution margin calculation

The contribution margin is calculated as the difference between the sales price and the cost of each product. Then, the contribution margin is allocated on every different variant. The analysis is made on a product family level and also on an A, B, C product and variant level.

The results indicate that the average CR for product A is 38,6%. The revenue of product A accounts for 48,1% of the total revenue of the product family and for 44,7% of the total contribution margin. The analysis also reveals that 88,3% of the total revenue comes from 50% of the product range. This raises questions regarding a reduction in the number of variants offered.

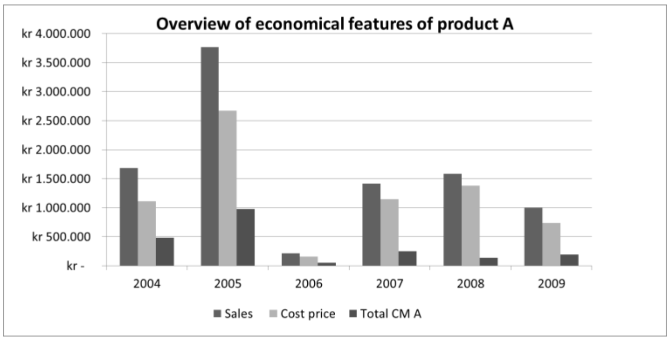


Figure 5-11 Overview of economical features of product A

Product B, with CR 48%, is the most profitable product within the family. It also accounts for 35% of the total revenue, 66% of the unit sales and 38,5% of the contribution margin. The analysis, furthermore, reveals that one variant accounts for 25% of the CR and the number of sales.

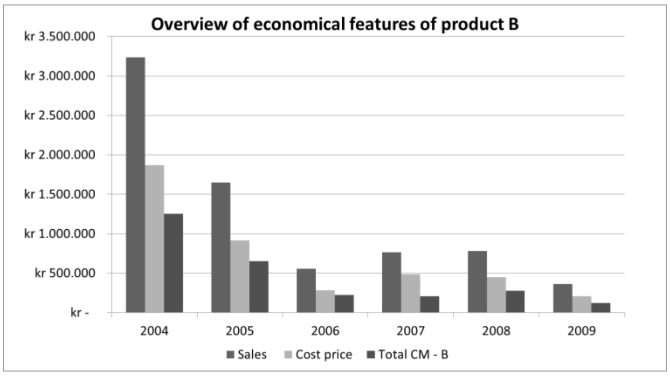


Figure 5-12 Overview of economical features of product B

The CR for product C is 37%, which accounts for 18,7% of the total revenue for the product family and only contributes 16,7% of the total contribution margin for the product family. Four variants are responsible for 82% of the revenue. Moreover, the newly introduced product C is not performing according to what was expected from the company, in spite of the fact that it applies the latest technology in product development and strong marketing techniques, which are expected to lead to a significant market share.

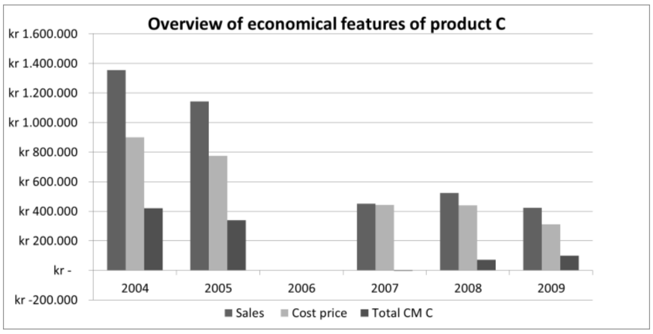


Figure 5-13 Overview of economical features of product C

The contribution margin is calculated based on the production costs. Based on the individual sales analysis of each product, the comparison reveals that the most profitable variant identified, is clearly product B.

5.4.3.2 Engineering Cost

When engineering hours are used, the contribution margin is directly affected because the customer is not charged directly for engineering hours used on a project. The overall cost of engineering from 2004–2009 is 851.877 DKK for known sales. As sales vary through the years, the total cost of engineering during this six years period does not give the right picture of the development for the product family. Therefore, it is more relevant to take a look at the total value of engineering resources used for the product family per year and divide that number by the total sales per year. The result is the average cost of engineering per unit sold, as displayed in the following figure.

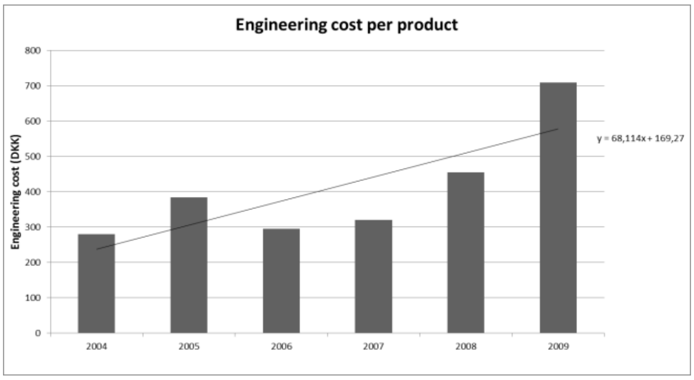


Figure 5-14 Engineering cost per piece

From these results, it is released that the engineering cost is increasing. Additionally, this increase indicates that the demand in specialized products is increasing through the years.

5.4.3.3 Sensitivity analysis

A sensitivity analysis is used to investigate the impact of different parameters. In this case study an important parameter to examine is the subsidiary mark-up. The sensitivity analysis explored how much it would mean for the company group in the course of five years if the subsidiary mark-up were 4%, 25 % or 35 %. The results are presented in the following table.

Table 5-8 Subsidiary mark-up

Year	2009	2008	2007	2006	2005
Sale	983	1400	1594	812	968
4,00%	-85	-895	-448	1306	673
4,51%	-36	-845	-374	1349	741
25,00%	598	-208	555	1920	1619
35,00%	922	118	1020	2223	2068

The negative numbers indicate that the subsidiary is delivering a deficit to the company. In this sense, the positive amounts show how much the company is earning on average on each sold unit. The subsidiary mark-up of 25% is the mark-up claimed by the head of the Netherlands subsidiary, backed up by sales personnel at the company.

5.4.4 Competitor analysis

Three main competitors, companies X, Y and Z, have been identified and analyzed. A comparison is made based on the characteristics of the competitive products resulting from the PVM attributes, such as product efficiency and weight, technical characteristics, delivery time and sale price. A part of the analysis is presented in the following table.

Table 5-9 Competitors' analysis

Comparison of efficiency and weight between company, X, Y, and Z					
	Static pressure [Pa]	Air flow [m3/s]	Efficiency [%]	Weight without motor [Kg]	Total list-price [Dkk]
A1	2700	10	81	604	105462
Similar product from X	2916	10	79	367	60950
	1808	8	81	461	66292
A2	1880	8	82	578	74773
A3	1880	8	82	718	103494
Similar product from X	1939	8	84	468	62010
Similar product from X	1916	8	82	320	44238
A4	778	21	68	1686	222924
Similar product from X	854	21	72	720	84387
A5	1693	21	74	1154	182811
Similar product from X	1854	21	83	720	102311
C1	516	10	54	187	34012
Similar product from X	369	10	51	320	37067
Similar product from X	467	10	86	720	70696
C2	2879	5	80	187	34012
Similar product from X	2847	5	81	*	29017
C3	3875	1	70	40	10420
Similar product from Y	4000	1	80	*	*
B1	1275	1	71	35	4399
B2	1275	1	75	40	8754
B3	1575	1	75	40	9215
Similar product from X	1430	1	81	27,5	5740
Similar product from X	1693	1	79	27,5	7966
Similar product from Y	1400	1	68	*	*
Similar product from Y	1700	1	52	*	*
C4	1691	8	80	187	34326
Similar product from X	1493	8	80	*	55513
C5	552	1	77	59	10314
C6	570	1	76	102	19751
Similar product from X	609	1	82	41	6823
Similar product from X	577	1	78	50	8951
B4	1421	2	69	98	13305
B5	1421	2	69	102	16238
B6	1421	2	78	121	24134
B7	1308	2	75	59	12329
Similar product from X	1424	2	75,5	34,2	6845
Similar product from X	1443	2	80,9	61	11457
C7	1691	8	80	187	34326
Similar product from X	1716	8	82	320	44238
Similar product from X	1649	8	78	*	35234
B8	921	2	72	89	9580
B9	921	2	72	98	12781
C8	921	2	80	84	14548
C9	880	2	77	102	20811
Similar product from Z	965	2	82,7	67,4	10374
Similar product from Z	967	2	81,4	91	13403
Similar product from Z	962	2	79,6	59	13759
B10	605	8	71	359	37667
B11	605	8	71	394	44713
Similar product from X	579	8	85,1	720	70696
Similar product from X	546	8	75	367	40368
Similar product from X	576	8	85,2	580	48918

The competitor analysis shows that company X is the largest player in the market and has a wide variety of products. Company Y has a smaller turnover compared to the studied company, but the products that company Y mainly focuses on are the ones that are competitive to A, B and C. Efficiency, weight and delivery time are the parameters that the product family under examination lacks. The analysis results in pointing out that the company under investigation is the weakest one in the market. However, the main advantage of the company is flexibility and service, even to the extent of fulfilling customer´s needs even though they do not fit its standard product range.

5.4.5 Market analysis

The market analysis is performed on a country level and is presented in the following figures for products A, B, and C. Due to a lack of data to establish a coherent customer analysis, this section focuses on assessing market shares.

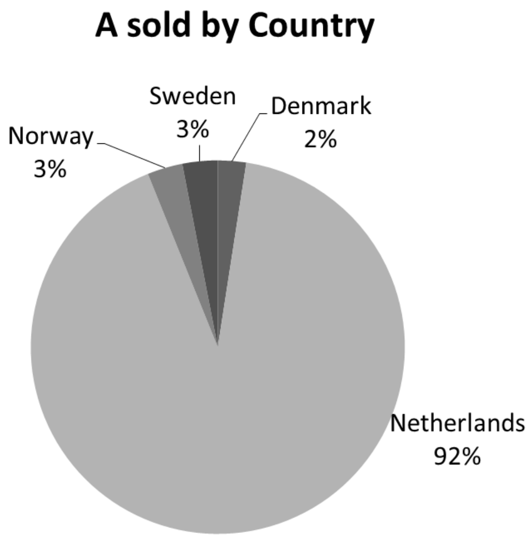


Figure 5-15 A products sold by country

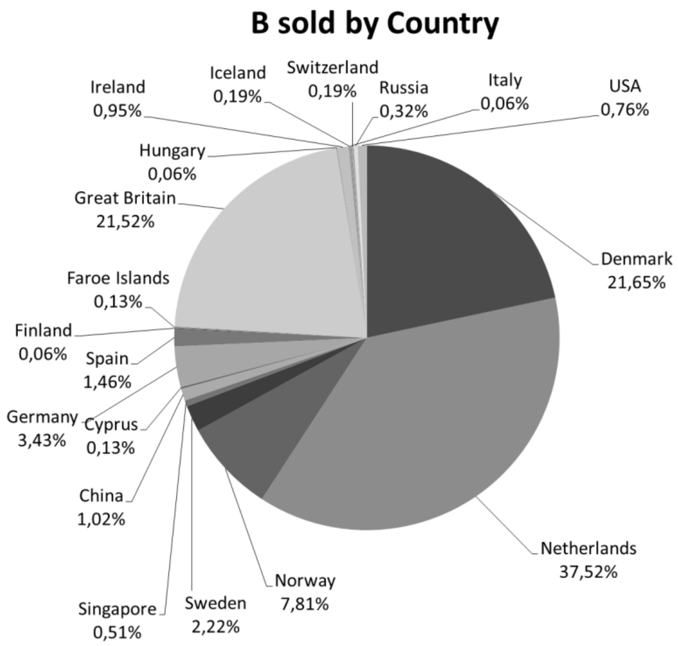


Figure 5-16 B products sold by country

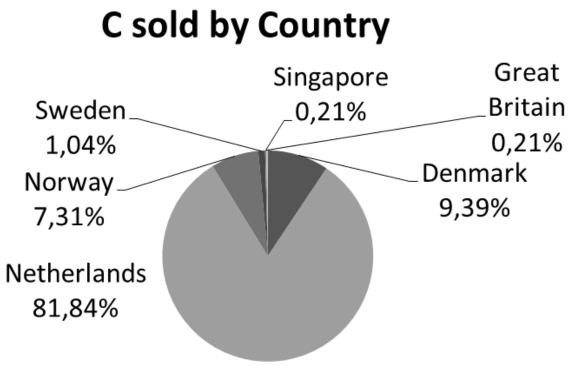


Figure 5-17 C products sold by country

It has been identified that although all three products are produced in Denmark, the percentage of their sales in Denmark is significantly lower than that in the Netherlands, where the main subsidiary is located.

Finally, the average estimated market share of the company and of its competitors is calculated. This results in a relatively low market share (1,5%) for the company for heating and ventilation products.

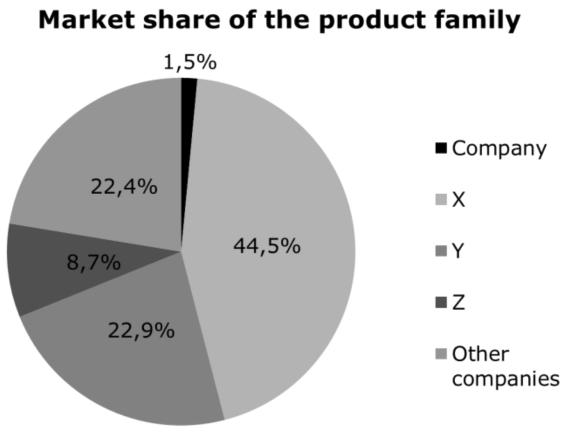


Figure 5-18 Market share

5.4.6 Scenarios for future product assortment

Although the product family has been redesigned following the principles of mass customization and standardization, there is a need for re-evaluation and further examination of the production set-up. As has been concluded from the previous two steps of the analysis, the company holds a relatively trivial market share compared to the competitors. In addition, the contribution margins of the three product families have been declining over the past six years. Based on these results, the development of the suggested scenarios focuses on overall cost reduction.

After assessing the results with the company's chief engineer some suggestions can be made. One possibility is to decrease the material use for parts of product A. Another would be standardizing components and decreasing the number of variants.

5.4.7 Decreasing the number of variants

From the PVM, it is identified that the fan is produced in four different positions, 0°, 90°, 180° and 270°. Each position has its own center height for each fan size. It can be seen from the information on the PVM that the center height for positions 90° and 180° is similar, and that positions 0° and 270° are closest to each other. Therefore, it is possible to have the same center heights for positions 90°and 180° and 0°and 270°. This means that the components connecting the fan house to the fan base can be decreased from 4 to 2, which results in decreasing complexity, both production- and assembly-wise.

5.4.7.1 Investment in a new machine

The plates for the variants produced at the company are cut with a laser cutter. After this operation, the remaining work required is welding. This operation for the product family under investigation is performed manually.

An investment in a robot welder is the second suggested scenario. However, such an investment of approximately 2.5 million DKK, is not affordable for the company. As a result the suggestion includes the robot welder to be used for all the product families produced by the company.

The total number of welding hours spent on manual work is calculated, along with the number of hours that will be saved by using the robot. The estimated annual cost reduction of the implementation of the robot welder is presented in the following table.

Table 5-10 Cost reduction by implementing the investment scenario

Investment in a new robot	
Initial investment (DKK)	2.500.000
Product family part	16,31%
Estimated cost reduction (DKK)	1.200.000
Investment ratio prod. fam. (DKK)	407.769
Cost reduction (DKK)	
A	51.917
B	31.563
C	37.532
Total cost reduction (DKK)	109.370

Based on the calculations the robot will be occupied for 16,31% of its time by the product family while the rest of the time will be used for the welding process of the other product families of the company. It can be seen from the table that the total cost reduction is not significant compared to the initial investment.

5.4.7.2 Stop the production

This scenario examines the benefits of stopping the production of the product family. There are two different options for the company in this case, either to sell the customer base or source similar products from competitors.

For the first option, it is required to estimate the future sales and sale values in order to calculate if this is an attractive solution for the possible buyers. This results in 1,25 million DKK earnings in the time horizon of five years for the potential customer. The following table summarizes the estimated earnings for the company when implementing the scenario of base selling.

Table 5-11 Company's side of NPV with sale with calculation rate of 11%

Year	0	1	2	3	4	5
Income (DKK)		521.543	578.913	642.593	713.278	791.739
Sales (DKK)	4.741.300					
	4.741.300	521.543	578.913	642.593	713.278	791.739
NPV (DKK)	**7.090.594**					

In order to explore and evaluate the second option, of outsourcing the product family, a comparison is made between the total cost of producing the products in-house, and the selling price for the competitors' products. Outsourcing is 19,2 % more costly for the company than producing its own products. The total costs are presented in the following table.

Table 5-12 Cost comparison

Outsourcing	In—house
73.301.165 DKK	61.479.904 DKK

5.4.8 The final decision

The previous steps allowed the company to become ready to take a decision for the future product assortment. First, the product family has been analyzed, in terms of technical characteristics and profitability. Then, an analysis of the customers and the competitors has been performed in order to place the company in its market position. Finally, three scenarios have been created and benefits and costs of each scenario have been quantified.

At that point, the suggested scenarios are presented to the company as recommendations for the future product assortment strategy. Based on the results of the scenarios and the feedback received, after the scenarios have been presented to a workshop in the company, the most feasible solution is to stop the production. If the company decides on outsourcing the variants from the competitors, it would only increase the contribution margin if the company can get a discount on the products they purchase from competitors of at least 16%, based on the cost calculations. As a result, the most profitable solution was to sell the customers' base, which increases the company's income directly.

5.4.9 Conclusions

This study presents the results from the application of the conceptual framework in a CTO manufacturer. The purpose of the framework is to be used as a tool in the decision making process of the product strategy. The scenarios presented for complexity management are built around overall cost reduction and focus on reducing both product and process complexity. The study is presented in Paper C and it contributes to answering RQ III.

5.5 Reconfiguring variety, profitability and postponement for product customization with global supply chains

5.5.1 Introduction

This study examines the relation between complexity in the product range and business process, by taking into account the production strategy (ATO, MTO, ETO) and global supply chain network. The company X is used in order to test the developed research question. In brief, the case company produces ATO, MTO and ETO products, it acquires two production sites, one in Denmark and one in China, and three distribution centers in Denmark, China and the USA. With reference to products distributed in Denmark, they are either produced entirely in Denmark or as SFU in China and assembled in Denmark.

The research questions under investigation are the following:

RQ1: How can the operational and financial performance of a supply chain network for customized products be improved?

This research question is answered based on the three sub questions:

RQ1.1: How can customized products be categorized relative to their degree of customization?

RQ1.2: How can the potential for a postponement of the CODP and a standardization strategy be identified?

RQ1.3: How can postponement and standardization effects on costs and contributions margins be quantified?

The following sections present the results of this research, which is presented in Paper D – Reconfiguring variety, profitability and postponement for product customization with global supply chains. The study also contributes to answering RQ III regarding managing and reducing complexity.

5.5.2 Analysis and results

Currently, the company categorizes the products as A, B and C based on their inventory turnover and their picking frequency. The results from this internal ABC analysis are presented in the following table.

Table 5-13 Internal ABC analysis

	Picking Frequency

Category	A (>20)	B (4-20)	C (0-3)
A (≥3)	18	2	0
B (2)	11	24	5
C (0-1)	3	46	190

The ABC categorization is based on internal experience. Products are categorized as A if they have inventory turnover higher than or equal to three and picking frequency higher than or equal to 20. B products are indicated by inventory turnover equal to two and picking frequency between three and 20. Finally, C products have inventory turnover less or equal to one and picking frequency less or equal to three. All the data refers to a 12-month period.

Both parameters, inventory turnover and picking frequency, are related to the sales volume of the products. However, with this internal categorization approach none of the measures accounts for the CM of the products. Yet according to the literature, in order to draw conclusions regarding the profitability of a product, the NR and production cost have to be taken into consideration. This results in questioning the accuracy of the internal ABC product categorization.

By implementing the suggested methodology, an ABC analysis is performed, which categorizes the products based on the NR and CM instead. The CM is calculated as the difference of the NR from the direct production cost, where direct production cost include the cost of material and labor. The following table presents the results of the ABC analysis.

Table 5-14 ABC product categorization based on CM and NR

		CM		
	Category	**A**	**B**	**C**
NR	**A**	38	23	11
	B	0	7	88
	C	0	0	132

When comparing the results from the two ABC analyses, it can be concluded that in the company's perspective many C products are kept in stock (81,6%), which leads to increasing inventory costs and consequently complexity costs. From the suggested ABC analysis the ratio of C products is relatively lower (77,3%). Yet the distribution of products varies between the two analyses, indicating that further research is required to identify the cause of this divergence.

To gain better understanding of how postponement may be applied, the results are displayed in relation to the three production strategies (ATO, MTO, ETO). In other words, the products are categorized into A, B or C, based on their NR and CM, revealing a significant difference between how the type of products that are included under each production strategy.

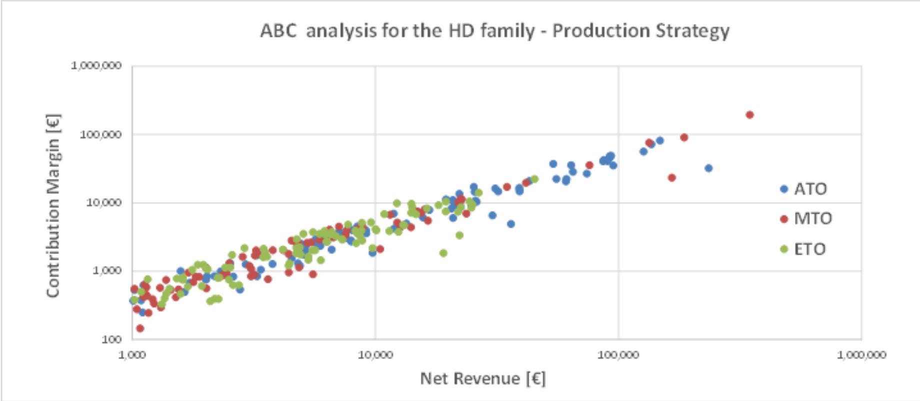


Figure 5-19 ABC product categorization by production strategy

As displayed in Figure 5-19 above, 60% of the ATO products are categorized as C products. 29% of the ATO variants are categorized as A, and the remaining 11% as B products. However, this result highly contradicts to the internal categorization of a product ATO. ATO products are standardized, produced in large batches and are high runners. That implies that ATO products have lower production cost and higher revenue, which would result in higher CM and, consequently, in an A product. Less contradictory, only 8% of the MTO belong to A and 87% to C products. Finally, as expected only 2% of the ETO products are A and 88% C.

In detail, the following table presents the total cost, net revenue, CM, number of variants and sales volume per production strategy.

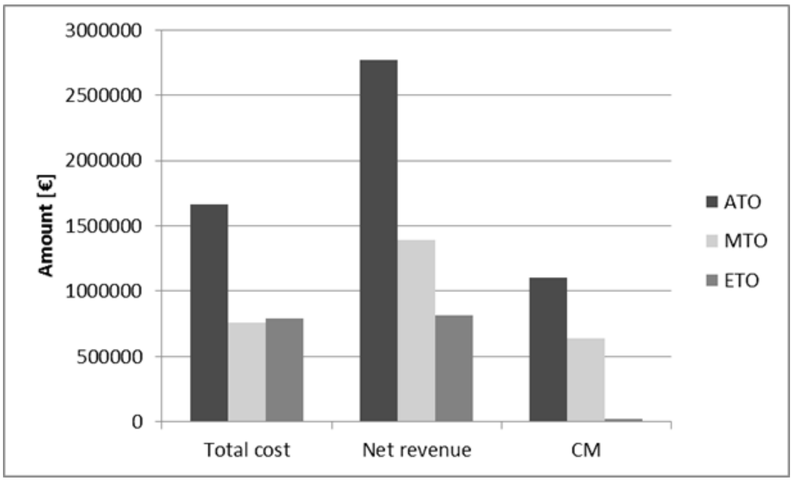


Figure 5-20 Comparison of the financial data from the three production strategies

The results from Figure 5-20 indicate that the ATO products are more profitable, contribute far more to the company's profitability and are sold in higher volume. However, this again does not conforms with the result from the internal ABC analysis (see Table 5-13), which shows that 60% of the ATO products are C. Based on the above, a re-categorization of the products under the three production strategies is recommended.

By following the suggested research method, two approaches are implemented. The first one aims at increasing the standardization of the ATO products. The company, as discussed above, uses SFU manufactured in China as pre-assemblies for the ATO products. The products including these SFU have significantly lower production cost. However out of the 97 ATO variants, only in 8% of the cases outsourcing through SFU's is used. The following Table 5-15 gathers the relevant financial data for the products produced in China and in Denmark.

Table 5-15 ATO products

Production country		Cost	NR	CM	# of variants	Sales volume
CH	sum	€ 8.826	€ 14.269	€ 5.444	8	273
	aver	€ 1.103	€ 1.784	€ 680	-	-
DK	sum	€ 109.347	€ 194.853	€ 85.505	89	1264
	aver	€ 1.229	€ 2.189	€ 961	-	-

To identify the potential for outsourcing, products with similar properties and sizes produced in Denmark and China are investigated. By increasing the number of SFUs used in the final assemblies, the overall number of variants produced is significantly reduced, thereby decreasing the complexity of the supply chain. The following Table 5-16 illustrates the results of those calculations.

Table 5-16 Financial data after implementing the SFU standardization

	Before	After	Difference
CM	€ 3.370.800	€ 3.388.987	€ 18.187
Revenue	€ 6.436.071	€ 6.076.030	€ -360.041
Cost	€ 3.065.271	€ 2.687.043	€ -378.228

For further product standardization, a re-categorization of the products among the three production strategies (ATO, MTO, ETO) is examined. Products with same sizes are analyzed based to their production strategy with the intention to move as many products as possible to the ATO category. Decisions are made after comparing the BOM and the functional properties of the products. This analysis results in increasing the standardization of 36 products, or 12% or the portfolio. In detail, 18 MTO and 18 ETO products are moved to ATO category. The financial impact is illustrated in the following figure.

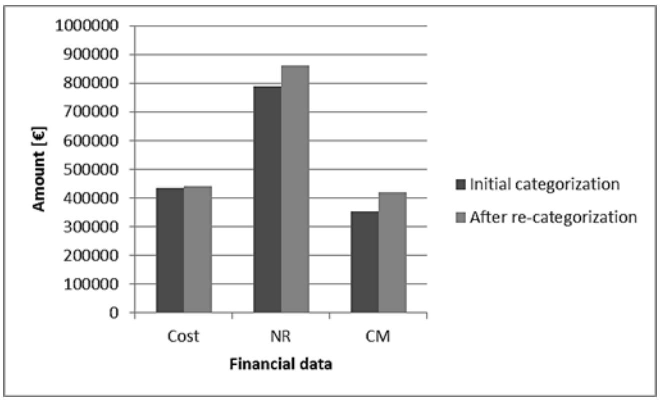


Figure 5-21 Comparison of financial analysis of the production strategy categorization

Summarizing the results from the two standardization methods discussed above, it can be seen that the total cost of the HD family is decreased by 4,3% . The impact of the implementation on the NR is not significant, due to the lower sales price the standardized products have compared to the customized ones. Yet, the increase in the CM by 18% (from 354.299 € to 419.314 €) indicates that the profitability of the new product portfolio has been positively affected.

Table 5-17 Total impact on the HD family

	Before	After	Total Impact
Total Revenue	€ 4.977.942	€ 4.996.389	0,4%
Total Cost	€ 3.212.839	€ 3.074.773	-4,30%
Total CM	€ 1.765.103	€ 1.921.616	8,9%

Next, the potential for substitution is being investigated. The analysis is made in 10 groups of products that have the same size. In particular 98 product variants are merged into 44, where 20 out of them are merged into 13 products that have SFUs produced in China as pre-assemblies. By merging the products, 54 variants can be eliminated, which additionally reinforces the standardization of the product family.

In order to estimate the total effect on the company's profitability after implementing the suggested method of both product standardization and variant substitution, a sensitivity analysis is performed. The following table describes the 4 combinations that are used in order to gain a better understanding of the impact of the approach on the CM of the product family.

Table 5-18 Sensitivity analysis with 4 scenarios

	A	B	C	D
Cost	-20%	-20%	-20%	-30%
Sales price	0%	-5%	-5%	-10%
Sales volume	5%	10%	0%	20%

For each of the above scenarios the cost, NR and CM are calculated. The results are as follows:

Table 5-19 Impact of the 4 scenarios

	1	2	3	4
Cost	- 3 %	- 2 %	- 4,1 %	-0,8 %
NR	1,8 %	1,7 %	-1,2 %	1,5 %
CM	10,5%	8,3 %	9,9 %	5,1 %

The negative percentages indicate that there is a reduction after the implementation of the suggested approaches. The results demonstrate that the CM is increased in every case. It worth mentioning that even in scenario 4, where there is no increase in the sales volume, the CM is increased considerably. As a result, the outcome of the sensitivity analysis indicates that the application of the suggested methods for product standardization and variant elimination have an impact on reduction of complexity costs and increase profitability.

5.5.3 Conclusions

The results of this study examine the relation of postponement and product substitution in regards to improvements in profitability and complexity management in a manufacturing company. The study points out how profitability and degree of customization of a product are related. Furthermore, the main parameters for decision making regarding the preferred product portfolio in terms of postponement and standardization are identified and quantified. The study is presented in Paper D and outcome contributes to answering RQ III.

5.6 Impact of product configuration systems on product profitability and costing accuracy

5.6.1 Introduction

This study examines the impact of implementing a PCS on the accuracy of the cost calculations during the early sales phase. Moreover the effect of the utilization of a PCS on the profitability of the products that are included in the configuration system is investigated. Aiming to explore these impacts, the following propositions were developed:

Proposition 1 *The accuracy of the cost calculations in the sales phase is increased by utilizing a PCS.*

Proposition 2 *Product profitability is increased by utilizing a PCS.*

A longitudinal field study is used as the research method and company XI, in the building sector with standard and special products, is providing the empirical evidence. The preliminary study is presented in Paper E and the revised and more detailed study in Paper I. The results of this study are supporting the answer for RQ III.

5.6.2 Analysis of the company's performance before and after implementation of the product configuration system

To compare the overall performance before the PCS was implemented (2009) and after the implementation (2011–2014), the CR is calculated for each project that was carried out at the company within the timeframe of this research. The CR is calculated as the ratio of the sales price and the contribution margin (CM), where the CM is the difference between the sales and the cost price. The cost prices of the projects are calculated as the sum of expenses, including construction site, subcontractors, materials and salaries. The formulas for the calculations of the CR and the CM are as follows (Farris et al., 2010):

Equation 5-3:

$$CR = CM \,/\, \text{Sales Price}$$

Equation 5-4:

$$CM = \text{Sales Price} - \text{Cost Price}$$

The deviation in the CR is calculated as the actual CR (calculated after the project was completed when all expenses are known) minus the estimated CR (calculated in the sales phase when the cost is estimated). The formula for calculating the deviation of the CR as follows:

Equation 5-5:

$$DEVCR = CRactual - CRestimated$$

If the real cost of the project is higher than the estimated cost, it results in negative deviation of the CR. Respectively, if the real cost of the project is less than the estimated, it results in positive deviation in the CR. Any deviation in the CR is something companies must be aware of. If the cost is overestimated, the company might lose the customer, and if the cost is underestimated, then revenue is lost.

The projects used for the comparison are from 2009, when only Excel spreadsheets were used to calculate the cost, until 2014. For the 2011–2014 period, the cost calculations were either performed in the PCS or by using Excel spreadsheets. Due to organizational resistance, not all salespersons used the PCS. In Table 5-20, the company's overall performance for 2009 and the 2011 to 2014 period is shown in terms of number of projects sold, the deviation in the CR and the average profitability.

Table 5-20 Overall analysis of the company's performance before the PCS was implemented (2009) and after (2011–2014).

Year	*No. of projects*	*Average DEV_{CR}*	*Average CR per project*
2009	55	−1.5%	25.0%
2011	117	−3.5%	27.2%
2012	90	−1.1%	28.5%
2013	116	−1.0%	28.2%
2014	168	−0.8%	29.0%

The analysis showed that the average CR steadily increased from 25.0% in 2009 to 29.0% in 2014. The implementation of the PCS was aimed to improve the company's CR by increasing the accuracy of the cost calculations in the quotations and thus the profitability of the projects. Furthermore, an additional functionality was included in the PCS that allowed the salespersons to set the desired CR for the project under question from an early stage of the sales process in order to make it easier to reach the goal.

Deviations in the CR also show positive improvements over the period as the average deviation was improved from −1.5% in 2009 to −0.8% in 2014. However, in 2011, the first year the PCS was utilized, the deviations in the CR increased considerably. This increase in deviations can be traced to the fact that the system had not been fully tested before the implementation and the users of the system lacked training. However, as the users became more experienced in using the system and errors were fixed, the PCS started providing valuable results.

This analysis indicates that the calculations are now more precise than before the implementation of the PCS and the company is moving closer to the targeted CR, and, consequently, the products' profitability is increasing. The results also highlight the importance of properly testing the system and training employees before the system is launched and fully functioning to avoid costly mistakes and to avoid resistance to using the system due to a lack of confidence.

5.6.3 Comparison of cost estimations and profitability between Excel and PCS

In this section, the yearly turnover, the CR of the projects and the deviations of the CR are analyzed and compared in terms of whether the initial quotation created during the sales phase was generated by the Excel spreadsheets or by the PCS. This comparison is possible because the PCS has not been accepted by all salespersons due to organizational resistance. Some still use Excel spreadsheets to generate quotations. The main reason is the lack of change management initiatives and the system being launched before it was fully tested, which resulted in some employees sticking to their old work habits (Forza & Salvador, 2002).

5.6.3.1 The contribution to yearly turnover

To increase the understanding of to what extent the PCS is used at the company, the yearly turnover for the projects was compared based on whether the quotation was generated with the PCS or the Excel spreadsheets.

In 2011, the first year the PCS was utilized in the company, the turnover for the products' quotations generated with the PCS was higher than the ones created with Excel spreadsheets. However, in 2012 the turnover for the products' quotations generated by using Excel spreadsheets was higher. In the first year the system was running, the lack of training and errors in the system affected its functionality. However, in 2013, the quotations generated with the PCS contributed more to the yearly turnover, and in 2014, this difference increased even more, indicating that the salespersons were using the system to a greater extent. Figure 5-20 shows the yearly turnover for the quotations created in Excel and by using the PCS.

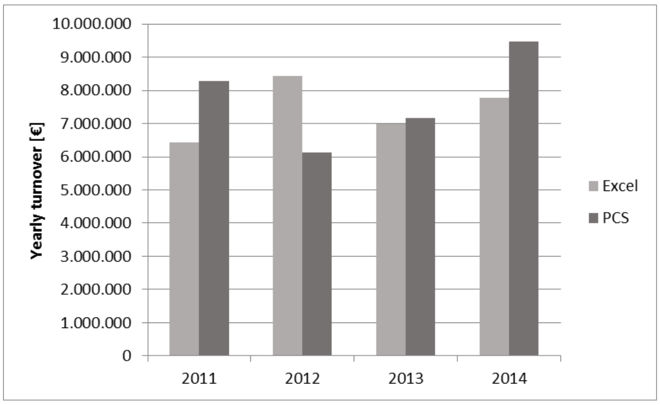


Figure 5-22 Comparison of turnover generated for quotations created in Excel and PCS.

However, no clear trend was identified in the comparison. As can be seen in Figure 5-22, in 2012, the projects handled by the salespersons with Excel spreadsheets contributed more to the company's turnover although the PCS had already been implemented. Some salespersons were reluctant to use the PCS in their working processes, as they still used Excel spreadsheets for calculating costs and generating quotations. Second, lack of training and errors in the system in 2011 might have given some salespersons the wrong impression of the usability of the system, which resulted in them not using the PCS in the following year. In detail, in 2011, 52% of the projects were handled with Excel spreadsheets to generate quotations, which corresponds to 47 out of 90 projects. The

2011–2012 period was the initial introduction of the PCS at the company, and the PCS did not include all products at that point; therefore, utilization was by definition limited. During the trial period, the turnover contributed by the projects handled in Excel was higher than the turnover from the projects handled in the PCS, but this changed significantly in the following 2 years. Thus, in the 2013–2014 period, when the company took greater advantage of the PCS, and its utilization was strongly established, the turnover of the projects worked out by using the PCS outnumbered the ones generated with Excel spreadsheets.

Overall, by comparing the yearly turnover of the projects handled through Excel spreadsheets and the PCS, no clear conclusion was reached. Thus, the next step of the analysis focused on identifying and comparing the CR for products sold via Excel and PCS.

5.6.3.2 Comparison of project profitability

To compare the profitability of the projects, the CR was used as it represents the ratio between sales prices and the CM, and a good indicator of project profitability. As previously explained, the company's goal for all projects is a CR of 30%, as a result of a strategic decision made in 2009 to increase the CR from 25% to 30%. The implementation of the PCS was aimed to reach the targeted CR of 30% for the projects. The analysis of the overall company's performance (Table 5-20) showed how the CR has increased since 2009. However, to confirm that this can be traced to the implementation of the PCS, a comparison of the CR of the quotations made by using the PCS and Excel spreadsheets was performed. In Figure 5-23, the actual CR (calculated based on the actual cost of the projects) is illustrated for the quotations created with the PCS and Excel.

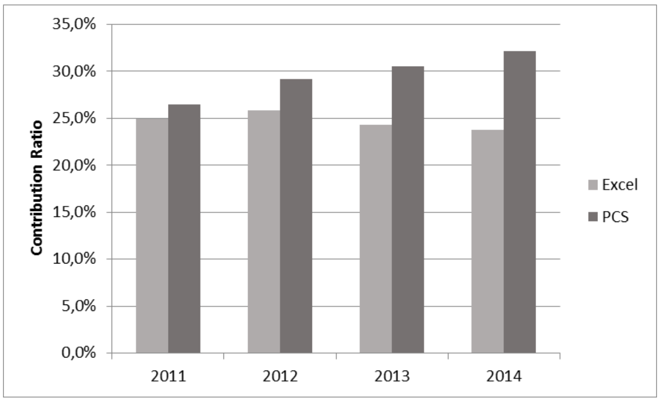


Figure 5-23 Comparison of CR for salespersons using Excel and PCS

Salespersons who used the PCS contributed a higher CR than those who used Excel spreadsheets. Furthermore, the gap in the CR increased between the salespersons who used the Excel spreadsheets and those who used the PCS. In 2014, the average CR was 29.0%; salespersons who used the PCS had an average CR of 32.1% while salespersons who used Excel spreadsheets had 23.8%. In other words, the salespersons who used the

PCS achieved a goal of 30%. The increasing gap between the CR for the quotations generated in the two systems can also be explained as a result of the increased utilization of the PCS and the company's effort to update prices in the PCS instead of the Excel spreadsheets. Finally, special products were not included in the PCS; therefore, to calculate the costs, Excel spreadsheets were always used. Although those products were not included in the calculations for the quotations made in Excel presented in Figure 5-23, they did not contribute significantly to the average CR. For example, for 2014 they affected the CR for the quotations created in Excel by only 0.2%. Therefore, the lower CR cannot be traced to special orders. This result confirms the second proposition formulated in this study: Product profitability increased when the projects are handled through a PCS.

5.6.3.3 Comparison of the accuracy of the cost calculations

To compare the accuracy of the cost calculations generated in the PCS and Excel spreadsheets, the DEVCR is calculated. The results are shown in Figure 5-24.

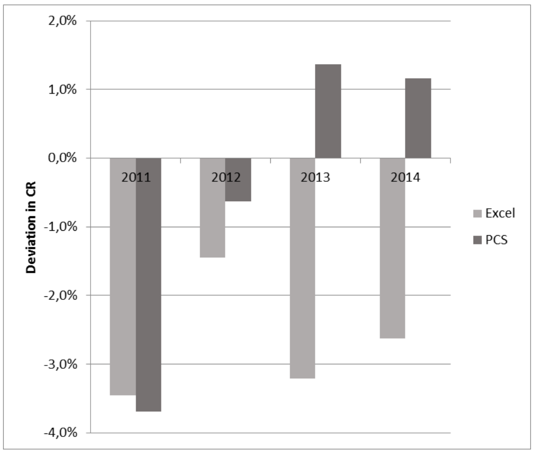


Figure 5-24 Comparison of deviations in CR for salespersons who used Excel and PCS

The CR showed less deviation for the products for which salespersons used the PCS than the CR for the products for which salespersons used Excel spreadsheets, with the exception of 2011. The deviation in the CR for the PCS in 2011 can be explained as a result of insufficient testing and a lack of training, which affected the performance in the first year after the implementation. In the following year, 2012, there was a significant reduction in deviations for quotations created via Excel spreadsheets and, mainly, for the ones created through the PCS. Moreover, in 2013 and 2014, the deviations in the quotations created by the PCS were positive (1.4% and 1.2%, respectively), while the deviations for the cost calculations generated with the Excel spreadsheets were negative and still quite high (–3.2% and –2.6%). Another possible explanation for the increasing gap between the CRs is the more complete cost calculations via the PCS than Excel spreadsheets. All parts required for every product were included in the PCS, while when the cost estimate was created in Excel spreadsheets, the salesperson might forget to include all of them. As a result, the estimated cost did not include all required parts and was lower than the actual cost, which led to the negative deviation in the CR. The analysis of the performance of the salespersons who used Excel and the PCS therefore indicates that the PCS affected the accuracy of the cost estimates and the CR positively, which supports proposition 1.

5.6.4 Conclusions

This study quantifies the impact of utilizing a PCS on product's profitability and accuracy of the cost estimations in the quotations during the sales phase. The results point out that the PCS provides significant improvements in the profitability of the products that are sold through it. Additionally, it takes into consideration the challenges of establishing the PCS as the only tool to be used by the salespersons. The reluctance of the employees to engage in utilizing the configuration system and discard the Excel sheets that had been used so far is discussed.

The study is presented in Papers E and I, and provides answer to RQ III regarding the control and reduction of the complexity.

5.7 Impact of the utilization of a product configuration system on product's life cycle complexity

5.7.1 Introduction

This study examines the impact of implementing a PCS in the early sales phases on the reduction of complexity, in terms of costs, in different phases of the product's lifecycle. The benefits and challenges of utilizing a PCS are discussed and the the following proposition is developed and tested in case study XII. The company selected as a case study in order to test the suggested proposition is an ETO manufacturer in the oil and gas industry.

Proposition 1 (P): Cost reduction is achieved through reducing complexity of a product's lifecycle processes by the use of a PCS.

The main proposition is divided into two parts, in order to be tested in the case study. The first one, studies the effect of reusing parts of completed projects to new ones. Then, a generalization of this concept is examined through the implementation of a PCS.

Proposition 1a (P1a): If it possible to reuse parts of the design of new projects from completed ones, then a significant reduction of costs of engineering, production and repairs after installation due to defects is achieved.

Proposition 1b (P1b): Application of PCS in the sales phase and increase of modular product range may lead to more standardized products and benefits proved in *P1a* indicate the scale of possible savings.

The preliminary results are presented in Paper F and the further elaborated in Paper J. The outcome of this study is contributing partly to answering RQ II and RQ III.

5.7.2 Problem analysis

An area of interest identified during the analysis of the financial performance of the projects is the reduction of cost through repetition. When a project is re-produced based on an existing one, several cost categories are identified to have noteworthy reductions.

Engineering costs, which are calculated based on the hours spent for each project or product, seem to benefit from re-using existing documentation. The following figure (Figure 5-25) illustrates the amount of hours spent on engineering for the pioneer project and for the projects reusing parts.

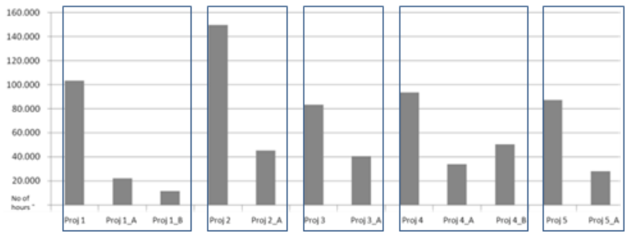


Figure 5-25 No of engineering hours spent on original projects and projects reusing parts

A trend can be seen, that for the projects that are replicated the engineering cost is always reduced. Only Proj 4_B, which is the second project created based on the initial Proj 4, is an outlier. This is explained by the fact that Proj 4_B is only partly a copy of the initial project.

The figure below (Figure 5-26) illustrates a similar effect on the production costs through reusability of existing material, such as drawings, instructions and documentation.

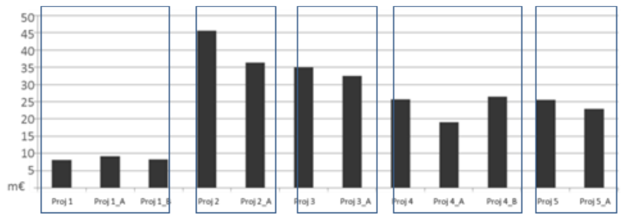


Figure 5-26 Production costs of original projects and projects reusing parts

Engineering and production costs account for more than 50% of the total cost, as explained before. As a result, these savings through re-usability and standardization of the processes could have a significant impact on the overall financial performance of the company.

Another cost area that showed significant savings in that aspect is the repairs after installation due to defects. The results can be seen in the following figure (Figure 5-27).

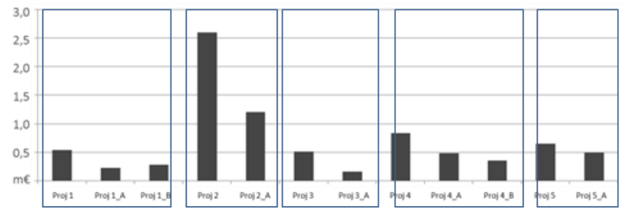


Figure 5-27 Costs of repairs after installation due to defects for original projects and projects reusing parts

This trend of cost reduction through reusability is also identified in other costs which are related to different life cycle processes, such as the revisions of drawings and changes on the drawings, outsourced production equipment and commissioning. The results from the figures above verify proposition 1a.

Nevertheless, deviations on the estimated costs and actual ones for the projects which are reusing parts is reported. Even though there is a significant reduction in various cost areas, still the company did not managed to reduce the cost to the desirable limit. And that is the reason why there is no profit gained for the sales of the projects.

5.7.3 Results and Methods for Improvement

Based on the analysis of the financial performance of the company two main areas of potential improvement can be identified as discussed in the literature by Jiao et al. (2007) and Blecker and Abdelkafi (2006); standardization and reusability. In order to achieve these improvements, firstly, the company should increase the standardization of the product portfolio. By changing or adjusting the products' architecture, the company can seize the benefits of complexity reduction in the product assortment. Then, the standardization of the processes and the increase in material reusability can be achieved by implementing a PCS. Through the utilization of a PCS both product and process complexity can be reduced and this would have a direct effect of cost savings.

In order to assess the potential benefits of suggested method, a sensitivity analysis is performed on the main cost areas, as they were identified in the section above. The table below (Table 5-21) indicates the main cost areas and the scenarios developed to estimate the potential benefits.

Table 5-21 Assessment scenarios

Cost areas	Conservative	Realistic	Optimistic
Engineering hours	5%	10%	20%
Production costs	10%	20%	30%
Repairs after	30%	50%	80%

installation

The scenarios are implemented to both the 12 projects and the 193 single products, which were also used for the analysis of above. The results of the sensitivity analysis are illustrated in the following table (Table 5-22).

Table 5-22 Scale of savings for the scenarios

Cost areas	Conservative	Realistic	Optimistic
Engineering hours [m€]	1,9	3,8	7,6
Production costs [m€]	33,6	67,2	100,8
Repairs after installation [m€]	2,8	4,5	7,1
Total [m€]	38,3	75,5	115,5

As it can be seen from Table 5-22 the potential savings in all the cost groups taking into consideration in the sensitivity analysis vary from 38,3 m€ for the conservative approach to 115,5 m€ for the optimistic scenario. These results showing significant potential for further cost reductions and the scale of possible savings, so they are aligned with the proposition 1b.

5.7.4 Conclusions

This study identifies how the costs vary among different projects in an engineering company with particular focus on the effect of having more standardized product designs in the projects. Moreover, it provides with an estimation of the scale of possible savings by utilizing a PCS in the early sales phase.

The study is presented in Paper F and J, and provides answer to RQ II and RQ III.

5.8 Evaluation of research outcome

This chapter presents the results from this research project and discussed the validation of the research. Validation is defined by Pedersen et al. (2000) as the acceptance of the usefulness of the research and its results. The suggested methods and tools developed based on the literature and experiences from practitioners are tested in several case studies. The empirical evidence contributes to the evaluation of the research project.

To begin with, due to several limitations and challenges discussed in sections 2.4 and 2.5, the suggested methods seek also validation from the literature. The literature research has indicated relevant less explored topics of interest within management of complexity. Based on the outcome of the literature study, the suggested methods and tools are formulated and developed. The research refers also to industrial standards.

To this end, it should be mentioned that during the RC stage of this research project a realistic goal for the desirable future is set. This goal is based on the collected evidence and refers to improvements on management on complexity in terms of profitability and efficiency. In order to achieve these goals, several methods and tools are developed. At the DS-I and DS-II stages of the research, these suggested solutions are applied in different case companies. The outcome of the case studies is aligned to the expected goal, defined at the first stage. These results presented in this chapter are used for validation of the applicability of the suggested methods for management of complexity.

The overall results are aligned to the expected outcome. This validation of applicability from the empirical evidence, combined with the confirmation in the literature is further discussed in the conclusions chapter, related to the theoretical and practical contribution.

The following table presents the different studies discussed in the results chapter in relation to the RQs, the empirical evidence and the appended articles.

Table 5-23 Summary of the six studies

Study		RQ	Article
1.	Complexity Cost Factors	RQ I – RQ1 RQ III	A, G
2.	Managing complexity of product mix and production flow	RQ II – P1	B, H
3.	Operational method for managing product variety	RQ III- P3	C
4.	Reconfiguring variety, profitability and postponement for product customization with global supply chains	RQ III – RQ2	D
5.	Impact of product configuration systems on product profitability and costing accuracy	RQ III – RQ3 - P4, P5	E, I
6.	Impact of the utilization of a product configuration system on product’s life cycle complexity	RQ II – P2 RQ III – RQ3 – P6	F, J

6 CONCLUSIONS

6.1 Contribution to research

This section gathers the formulated RQ and the results of the research. Each RQ is answered by the different papers and cases.

The overall research objective of this project is :

Research objective:
Improve management of complexity in a manufacturing organization

In order to provide a concrete answer, the research objective is divided into three parts, which are answered below. The management of complexity within an organization can be performed taking into account the following areas:

- identification of complexity,
- relation between product and process complexity,
- methods to control the factors responsible for causing complexity and reducing the related complexity costs

Each of the main RQs (I, II, III) focuses on those three different aspects of complexity management. The RQs and the answers are presented below.

RQ I. How can complexity in products and processes be identified?

1. *RQ1:* Which CCFs identified from the literature may be used to identify and quantify complexity costs in a manufacturing company?

The answer to this RQ is provided by Paper A. In that paper a literature research is conducted in order to identify the relevant factors discussed by other research groups. Based on that, a list of factors that are responsible for increasing complexity costs is created. The factors are categorized according to the business process they relate to. Then, empirical evidence supports the results of the literature review. In the case studies the list of factors is used as a checklist in order to identify relevant areas of complexity.

RQ II. How to analyse the correlation between product and process complexity?

To answer RQ II the following propositions are formulated. The first proposition (P1) suggests a tool for a systematic approach of management of complexity. The second proposition P2 examines the relationship between product and process complexity, more specifically how a change on the product affects the processes in terms of complexity.

1. *Proposition 1 (P1):* Substitution on a module and component level contributes to improving of the production flow and capacity utilization of machinery and inventory.
2. *Proposition 2 (P2):* If it possible to reuse parts of the design of new projects from completed ones, then a significant reduction of costs of engineering, production and repairs after installation due to defects is achieved.

In order to provide answer to the second RQ two papers are used, Paper B and Paper F.

In Paper B, the relationship between product and process complexity is examined. In detail, the research focuses on examining the production flow and capacity utilization in relation to the product assortment (number of products, numbers of components). The analysis concludes that product complexity has an impact on process complexity. In detail, the results of this case study indicate that by reducing the number of components to be produced, the process flow is optimized, especially in bottleneck machinery, as well as the stock capacity is improved.

In Paper F, the results show that by increasing reusability of design parts from finished projects to new ones is responsible for reducing costs in several life cycle processes. The outcome of this case study indicates that the standardization of products is directly related to improvements in the engineering, production and after-sales process of future products. This indicates that by reducing complexity in the product, the process complexity is also reduced, in terms of time allocation and costs.

By combining the results from Paper B and F this research shows that there is a correlation between product and process complexity. The outcome of the case studies indicates that there is a direct effect from decreasing product complexity through standardization and product variant management to decreasing process complexity, by achieving process standardization and optimization.

RQ III. How to reduce complexity in a manufacturing company?

The answer to RQ III is provided by papers C, D, E, F and G. Each of the following sub-questions and propositions are supported by the empirical evidence from the case studies. This question is divided into three main parts. The first one tests an operational method for management of complexity in the future product assortment (P3).

3. *Proposition 3 (P3):* The four step operational method attempts to guide a systematic approach of product scoping, profitability analysis for CTO products, customers and competitor analysis and scenario creation for future product assortment.

Paper C presents the four step operation method to manage complexity within an organisation. The first step includes the analysis of the product assortment and identification of the product that should be considered for further investigation. The second step analyses the profitability of the products that fell into the scope of the analysis by analysing their sales volume and price, relevant costs and contribution margin. This step provides information for the decision making regarding the future product assortment. The third step focuses on market and competitors analysis. The results of the third step demonstrate the competitive advantages of the company regarding their customers and the competitive products. Based on these result, strategic decision can be made in terms of the focus of the future product portfolio. The fourth step develops initiatives for the future product assortment, based on the results from the previous steps. The suggested initiatives are created aiming for reduction of product and process complexity, by increasing standardization.

The second part of RQ III examines the performance of the supply chain in accordance to product complexity. Production strategy, postponement and standardization are the aspects examined in relation to the profitability of the products.

4. *RQ2:* How can the operational and financial performance of a supply chain network for customized products be improved?
   a. *RQ2a:* How can customized products be categorized relative to their degree of customization?
   b. *RQ2b:* How can the potential for a postponement of the CODP and a standardization strategy be identified?
   c. *RQ2c:* How can postponement and standardization effects on costs and contributions margins be quantified?

Paper D is used to provide an answer this RQ. The results from the case study indicate that by performing an ABC analysis based on CM and NR should also be related to the CODP. This enables a better categorization of the product variants based not only on their profitability but also on their degree of customization.

In order to improve product standardization the optimal CODP should be identified. For achieving that, the analysis of the sales volume, profitability, production strategy, product’s interfaces and BOM should be defining the preferred product portfolio.

After selecting the preferred product portfolio the potential savings should be estimated in order to make a strategic decision. The suggested initiatives are developed based on improving standardization of the product assortment, product substitution and postponement. By performing a sensitivity analysis of the new cost, sales price and sales volume on the estimated NR and CM , the benefits can be quantified.

In conclusion, product and process standardization, through increasing substitution and modularity, and allocating the optimal production strategy, has an effect on complexity through the supply chain. To this end, reduction in product and process complexity leads to an improved operational and financial performance of the supply chain.

The last part of the study of complexity reduction addresses the use of a product configuration system as a tool to reduce complexity and improve profitability of the product portfolio. The last question is formulated (RQ3) and it is tested in the three following propositions (P4, P5, P6).

5. *RQ3:* How a product configuration system can improve the profitability of the product assortment in a manufacturing organisation?

The remaining three propositions P4, P5 and P6 are focusing on complexity reduction

d. *Proposition 4 (P4):* The accuracy of the cost calculations in the sales phase is increased by utilizing a PCS.
e. *Proposition 5 (P5):* Product profitability is increased by utilizing a PCS.

Papers E and I provide empirical evidence to support P4 and P5. In order to improve the standardization and efficiency of the sales process, a PCS is utilized. The products included in the PCS have increased CM, which shows increased profitability. Additionally, the accuracy of the cost estimations at the early sales phase is improved for the products sold through the PCS. By testing P4 and P5 in a case company is concluded that reduction of complexity in the sales process is achieved by implementing a PCS due to increase standardization.

f. *Proposition 6 (P6):* Cost reduction is achieved through reducing complexity of a product's lifecycle processes by the use of a PCS.
    i. *Proposition 6a (P6a)*: Application of PCS in the sales phase and increase of modular product range may lead to more standardized products and benefits proved in P1a indicate the scale of possible savings.

P6 is tested in Papers F and J. The results show that the implementation and utilization of a PCS can be used as a tool to reduce complexity both in products and processes. Firstly, products that are included in the PCS are more standardised by having a modular design. Then, several lifecycle processes are benefited by this increased product standardisation, leading to increased efficiency and cost reduction. This study shows that the utilization of a PCS has a positive effect on complexity reduction in both products and processes.

In addition to the results from P1, RQ2 and RQ3, the outcome of Paper G contribute to provide an overall answer to the RQ3. The two main concepts discussed in the literature are presented and applied in seven case studies. In detail, reduction of product complexity is implemented through reduction of product range, elimination of variants, standardization of the portfolio, reusability in product design and substitution on both finished good and component level. Regarding process complexity, the initiatives implemented are process optimization, distribution of products and inventory management.

In conclusion, the methods tested in the case studies indicate that complexity reduction can be achieved by assigning the right degree of customization to each product variant. Postponement and standardization may lead to profitability improvement of the product portfolio. Process standardization through the product's life cycle can benefit from the implementation of a PCS in the early sales phase. However, in order to identify the relevant products to be considered for improvement, analysis of the current profitability state and market is required.

In order to provide an overall answer to main RQ the conclusions from the three sub-questions are gathered. Firstly, relevant factors that are responsible for complexity costs have to be identified. Then the relationship between product and process complexity has to be analysed. Finally, initiatives should be taken so as to improve standardization of products and processes. The following table presents the RQs, the empirical evidence and the articles used to provide answers.

Table 6-1 Summary of theoretical contribution

RQ	Sub-questions and Propositions	Study	Case company	Article
I	RQ1	1	I ,II, III,IV, V,VI, VII	A, G
II	P1 P2	2 6	VIII XII	B, H F, J
III	P3 RQ2 RQ3 - P4 - P5 - P6	1 3 4 5 6	IX X XI XI XII	G C D E, I E, I F, J

6.2 Contribution to practice

This research project is supported by empirical evidence and the main results are the outcome from implementing the suggested methodologies on 12 case studies. Based on that, the main contribution to the practitioners is the identification of CCFs and the initiatives for complexity reduction.

The list of CCFs identified from the literature and tested in 7 companies can be used as a checklist. The companies that have been selected for that study cover a wide range of industrial sectors. In each case company the list of CCFs is used as a starting point of identifying relevant areas where complexity costs can be hidden. This list provides a structured approach for practitioners to recognise and categorise factors in different companies that are responsible for complexity costs.

In all 12 case studies initiatives for controlling and reducing complexity have been developed. These initiatives are aiming to improve product and process standardization. As the case companies and the products vary significantly among all the projects, the initiatives are developed based on two main concepts.

The first goal is to improve the product assortment by increasing modularity and identifying possibilities for substitution. This leads to a preferred product assortment and reduced product complexity. Then, the second concept is concerned with process standardization. Identification of the optimal production strategy and CODP, and utilization of a PCS are the main tools that have a direct effect on increasing process standardization and reducing complexity through the product's life cycle.

The identification of CCFs and the methods for development of initiatives for complexity reduction are the main contribution to practitioners, as they provide a concrete tool for a complexity reduction program. This structured approach can be used by companies in different industrial sectors, with different product portfolios, and assist managers across organizational units on the strategic decision making for the future product assortment.

6.3 Further research

Through this research project several opportunities for further research subjects have arisen. Reflecting on the methods, the results and the conclusions of this research project the following areas of interest for future research are identified.

To begin with, one of the main concepts for reducing product complexity is through product substitution. A more structured method for product substitution can be developed. In the current project the substitution is suggested based on analysis of BOM, sales volumes, financial analysis, production strategy and taking into account the product architecture. However the analysis and the decision making process on the how products can be substituted is performed manually. This process can be standardized by developing an optimization tool for analysing and concluding on the substitution decision making process. This could also be related to establishing more explicit criteria for both identifying and scoping potentials product groups to analyse and assess the suggested scenarios.

Another area of interest for future research is to include more longitudinal studies to validate the estimations from the initiatives for reducing complexity. In the current research project, one longitudinal case study has been performed regarding the accuracy of cost estimations before and after the utilization of a PCS. This can be further extended in order to validate the reduction of complexity in products and processes after implementing the suggested initiatives.

The last main topic of interest arose from this research project is related to the utilization of the PCS. In the case studies that a PCS is utilized as a tool for complexity control and reduction, a resistance from the employees was considered to be a main barrier in the change process. To this end, it would be relevant to extent the research in developing methods to introduce and establish the change process, especially regarding the utilization of a PCS. This should include not only managerial aspects, but also practical tools for practitioners to facilitate a smooth transition to a new working routine.

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8 APPENDED PAPERS

ARTICLE A

ARTICLE B

ARTICLE C

ARTICLE D

ARTICLE E

ARTICLE F

ARTICLE G

ARTICLE H

ARTICLE I

ARTICLE J

ARTICLE A

Identification of complexity cost factors in manufacturing companies

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Abstract

Complexity tends to be arguably the biggest challenge of manufacturing companies. As the demand from the customers increases in volume and diversity, the number of finished products and components increases as well. This increasing product complexity has a direct effect on the production processes. This research focuses on the relation between product and process complexity. Complexity cost factors are identified and categorized under the industrial standard APQC for process classification. Then, this categorization is used as a tool for identification of complexity cost factors in seven companies. The results from this research are evaluated and future work is discussed.

Keywords: Process Complexity, Product Complexity, Complexity Cost Factors

Introduction

Complexity is a field of increasing interest during the latest years, both for researchers and practitioners. Recent surveys show that the main concern of 1,500 chief executive officers (CEOs) is the increasing complexity, which is considered to be the biggest threat for an organization (IBM, 2015). A survey performed in over 100 companies from more than 10 industrial sectors revealed that 84% of the companies consider complexity as a key cost factor, and that lack of transparency over complexity costs leads to inefficient management of complexity (ATKearny, 2009). Complexity is three-dimensional, as it rises in products, processes and organizational structure, and there is an interconnection and a strong impact among these three types of complexity (Wilson and Perumal, 2009).

Complexity in the products leads to complexity in operations (Blecker et al., 2006). In this article we mainly focus on costs implications from product complexity on production, delivery and sales order handling (Samy and ElMaraghy, 2012a). Additionally, we neither consider other implications like on time delivery, time of delivery, quality, ability to introduce new products, nor the process step of product development. In order to make an in depth analysis, only parameters addressing costs are taken into account (Wang et al., 2011). Aiming to quantify the impact from product complexity we need to relate a specific product assortment with a specific number of components and number of finished goods and quantify the impact from reducing or increasing the number of components or number of finished goods on the costs of a specific process step. A CCF is a factor that describes how product complexity (e.g. number of finished goods) has an impact on the costs of a specific process step. Examples of CCFs are setup times in production, scrap of materials in setup of machines, sales order handling, inventories of finished goods, and freight of finished goods to warehouses.

The assessment of product profitability and cost behavior (Wan et al., 2012) has been discussed in terms of managing complexity product- and process- wise (Danese and Romano, 2004) (ElMaraghy et al., 2013). Hence the purpose of this paper is to identify and classify possible CCFs in manufacturing companies. Then, CCFs are grouped and categorized under the APQC industrial standard of process classification (APQC, 2015), in order to provide an overview and a practical approach for identification in a specific company. These factors identified are further to be used for analyzing and quantifying costs caused by complexity in manufacturing companies. The results of this research contribute to the development of an approach for managing complexity in manufacturing companies, in addition to product variety control and optimization of production processes.

Theoretical Background

In order to define the conceptual framework of this research, a literature review is performed. The main key words for searching are "complexity cost factors", "product complexity", "process complexity" and "complexity cost drivers". The reason for introducing the term "driver" is the fact that early in the review process, it has been noted that many articles use this term within the same meaning as others use the term "factor", such as Perona and Miragliotta (2004) and Schaffer and Schleich (2008). However, both words when used in the articles reviewed refer to facts that cause, stimulate and increase complexity.

The second part of the literature review focuses on identifying a framework of classification of processes. The reason for using such a framework is to obtain an overview of the processes in a manufacturing environment, in order to enable comparison among organizations and categorize the CCFs under the relevant processes. The industrial standard APQC provides such a process classification (APQC, 2015). The reason for selecting the APQC standard as a classification framework is that it describes all the processes in every industrial environment; as a result it can be applied to any manufacturing company.

To begin with, five areas of complexity are identified by Foster and Gupta (1990): product design, procurement, manufacturing process, product range, and distribution. Rommel et al. (1993) identifies and calculates the complexity costs for the business processes, by using a case study in the automobile manufacturing. The research concludes with the cost structure and the break-down of complexity costs to different processes. 15-20% of the total costs are complexity costs, which are allocated to several business processes, such as inventory, production, logistics and sales.

Blecker et al (2004) discuss the relations between mass customization and complexity. Mass customization principles are investigated from two different perspectives. On the one hand, when applied as a pure customization strategy, they increase the product variety, which results in high planning and scheduling complexity. On the other hand, as customer ordering decoupling point moves towards the front-end, then mass customization reduces product configuration and inventory complexity.

Wildemann (2001) performs an empirical study in manufacturing industries, regarding how the number of product variants affects the unit costs. Two types of industries are examined, with traditional and segmented and flexible automated plants. The results have shown that with the double number of product variants in the production program, the unit costs would increase about 20-35% for industries with traditional manufacturing systems. At the same time, in segmented and flexible automated plants, the unit costs would increase about 10-15%.

In tandem with these results, Khurana (1999) categorizes various production processes, such as job shops, flow shops, assembly and continuous processing, by assigning levels of product and process complexity.

Another distinction among complexity factors is their predictability and controllability. Gershwin (1994) categorizes as controllable activities maintenance, setup changes and calibration, while activities that increase complexity, though are unpredictable, could be failures, vendor non-delivery and worker absence.

The following tables (1-5) provide an overview of the results from the literature review. Each table describes the CCFs related to a process group, as described in the APQC standard. Under each CCF, the authors working with it are listed. When the names are in bold, it means that the article provides with quantification methods. When parenthesis follows the name of the authors, it represents that there is empirical evidence, such as case-study (CS), survey (S) or numerical example (NE).

Table 1 - Plan for and align supply chain resources

No of components
No of material handling systems: **Kuzgunkaya & ElMaraghy, 2006** (CS), **Samy & ElMaraghy, 2012b** (CS), **Garbie & Shikdar, 2011b** (NE), **ElMaraghy et al., 2012** (CS)
State of material handling systems: **Kuzgunkaya & ElMaraghy, 2006** (CS), **Samy & ElMaraghy , 2012b** (CS)
Type of material handling systems: **Kuzgunkaya & ElMaraghy, 2006** (CS), **Garbie & Shikdar, 2011b** (NE), **Samy & ElMaraghy , 2012a** (CS)
Material flow pattern: **ElMaraghy et al., 2014** (CS), **Samy & ElMaraghy, 2012b** (CS), **Thyssen et al., 2006** (CS), **Garbie & Shikdar, 2011b** (NE), Hayes & Clark, 1985 , Urbanic & ElMaraghy, 2006 (CS), Khurana, 1999
No of finished goods
No of material handling systems: **Kuzgunkaya & ElMaraghy, 2006** (CS), **Samy & ElMaraghy, 2012b** (CS), Sivadasan et al., 2002 (S), **Garbie & Shikdar, 2011b** (NE), **Samy & ElMaraghy, 2012a** (CS), **Schaffer & Schleich, 2008** (CS)
State of material handling systems: **Kuzgunkaya & ElMaraghy, 2006** (CS), **Samy & ElMaraghy, 2012a** (CS)
Type of material handling systems : **Kuzgunkaya & ElMaraghy, 2006** (CS), **Garbie & Shikdar, 2011b** (NE), **Samy & ElMaraghy, 2012a** (CS)
Material flow pattern: **ElMaraghy et al., 2014** (CS), **Samy & ElMaraghy, 2012b** (CS), Sivadasan et al., 2002 (S), **Garbie & Shikdar, 2011a** (CS), **Garbie & Shikdar, 2011b** (NE), **Schaffer & Schleich, 2008** (CS), **Rathnow, 1993** (CS)

Table 2 - Procure materials and services

No of components
No of suppliers: **ElMaraghy et al., 2012, Hu et al., 2008, Perona & Miragliotta, 2004** (CS), **Jacobs, 2013**
Location of suppliers: **Hu et al., 2008**

No of finished goods
Location of suppliers: **Hu et al., 2008**
No of suppliers: **Garbie & Shikdar, 2011a** (CS)**, Garbie & Shikdar, 2011b** (NE), **Perona & Miragliotta, 2004** (CS)**, Jacobs, 2013**
Cost of sourced components: **Foster & Gupta, 1990** (CS)

Table 3 - Produce/Manufacture/Deliver product

No of components
Capacity utilization : **ElMaraghy et al., 2012, Garbie & Shikdar, 2011b** (NE), Blecker & Abdelkafi, 2006
Assembly: **ElMaraghy et al., 2012, Hu et al., 2008, ElMaraghy et al., 2014** (CS)**, Samy & ElMaraghy, 2012b** (CS), **Thyssen et al., 2006** (CS)**,** Blecker & Abdelkafi, 2006**, Samy & ElMaraghy, 2012a** (CS)**, Khurana, 1999**
Tools: **Hu et al., 2008, Samy & ElMaraghy, 2012b** (CS)**, Deshmukh et al., 1998** (NE), Urbanic & ElMaraghy, 2006
Operator: **Hu et al., 2008,** Urbanic & ElMaraghy, 2006 (CS)**,** Gershwin, 1994
No of machines: **Kuzgunkaya & ElMaraghy, 2006** (CS)**, ElMaraghyet al., 2014** (CS)**, Samy & ElMaraghy, 2012b** (CS)**, Garbie & Shikdar, 2011b** (NE)**, Deshmukh et al., 1998** (NE), **Perona & Miragliotta, 2004** (CS)**, Samy & ElMaraghy, 2012a** (CS)**,** Urbanic & ElMaraghy, 2006 (CS)
Type of machines: **Kuzgunkaya & ElMaraghy, 2006** (CS)**, Garbie & Shikdar, 2011b** (NE)**, Samy & ElMaraghy, 2012a** (CS)**,** Urbanic & ElMaraghy, 2006 (CS)
State of machines: **Kuzgunkaya & ElMaraghy, 2006** (CS)**, Samy & ElMaraghy, 2012a** (CS)
No of buffers: **Kuzgunkaya & ElMaraghy, 2006** (CS)**, Samy & ElMaraghy, 2012a** (CS)**, Samy & ElMaraghy, 2012b** (CS)**, Khurana, 1999**
Type of buffers: **Kuzgunkaya & ElMaraghy, 2006** (CS)**, Samy & ElMaraghy, 2012a** (CS)
State of buffers: **Kuzgunkaya & ElMaraghy, 2006** (CS)**, Samy & ElMaraghy, 2012a** (CS)
Failure: **Kuzgunkaya & ElMaraghy, 2006** (CS)**, Samy & ElMaraghy, 2012b** (CS)**,** Hayes & Clark, 1985**, Urbanic & ElMaraghy, 2006** (CS)**,** Gershwin, 1994
Set up: **Thyssen et al., 2006** (CS)**, Garbie & Shikdar, 2011b** (NE), **Deshmukh et al., 1998** (NE), **Benjaafar et al., 2004,** Hayes & Clark, 1985**,** Urbanic & ElMaraghy, 2006 (CS)**,** Gershwin, 1994
Change-over: **Thyssen et al., 2006** (CS)**, Garbie & Shikdar, 2011b** (NE), **Deshmukh et al., 1998** (NE), **Benjaafar et al., 2004,** Hayes & Clark, 1985**,** Urbanic & ElMaraghy, 2006 (CS)**,** Gershwin, 1994
Waiting times: **Thyssen et al., 2006** (CS)**, Garbie & Shikdar, 2011b** (NE), **Deshmukh et al., 1998** (NE), Hayes & Clark, 1985**,** Urbanic & ElMaraghy, 2006 (CS)**,** Gershwin, 1994
Batch size: **Thyssen et al., 2006** (CS)**, Garbie & Shikdar, 2011b** (NE), **Deshmukh et al., 1998** (NE), **Benjaafar et al., 2004**
Capital costs (rent/heating): **Thyssen et al., 2006** (CS)**, Perona & Miragliotta, 2004** (CS)
Production lines: **ElMaraghy et al., 2012, Kuzgunkaya & ElMaraghy, 2006** (CS)**, Hu et al., 2008, Garbie & Shikdar, 2011b** (NE), Blecker & Abdelkafi, 2006**, Deshmukh et al., 1998** (NE), **Jacobs, 2013**
Job shop: **Deshmukh et al., 1998** (NE), **Khurana, 1999**

<u>*No of finished goods*</u>
<u>*Capacity utilization*</u>: **ElMaraghy et al., 2012, Hu et al., 2008, Garbie & Shikdar, 2011b** (NE), Blecker & Abdelkafi, 2006 <u>*Assembly*</u>: **ElMaraghy et al., 2012, Hu et al., 2008, Samy & ElMaraghy, 2012a** (CS), Blecker & Abdelkafi, 2006**, Samy & ElMaraghy, 2012b** (CS)**, Schaffer & Schleich, 2008** (CS) <u>*Tools*</u>: **Hu et al., 2008, Samy & ElMaraghy, 2012b** (CS)**, Garbie & Shikdar, 2011b** (NE), **Deshmukh et al., 1998** (NE) <u>*Operator*</u>: **Hu et al., 2008** <u>*No of machines*</u>: **Kuzgunkaya & ElMaraghy, 2006** (CS)**, ElMaraghy et al., 2014** (CS)**, Samy & ElMaraghy, 2012a** (CS), Sivadasan et al., 2002 (S)**, Garbie & Shikdar, 2011b** (NE)**, Deshmukh et al., 1998** (NE)**, Samy & ElMaraghy, 2012b** (CS) <u>*Type of machines*</u>: **Kuzgunkaya & ElMaraghy, 2006** (CS)**, Garbie & Shikdar, 2011b** (NE)**, Samy & ElMaraghy, 2012a** (CS) <u>*State of machines*</u>: **Kuzgunkaya & ElMaraghy, 2006** (CS)**, Samy & ElMaraghy, 2012a** (CS) <u>*No of buffers*</u>: **Kuzgunkaya & ElMaraghy, 2006** (CS)**, Samy & ElMaraghy, 2012a** (CS)**, Samy & ElMaraghy, 2012b** (CS) <u>*Type of buffers*</u>: **Kuzgunkaya & ElMaraghy, 2006** (CS)**, Samy & ElMaraghy, 2012a** (CS) <u>*State of buffers*</u>: **Kuzgunkaya & ElMaraghy, 2006** (CS)**, Samy & ElMaraghy, 2012a** (CS) <u>*Failure*</u>: **Kuzgunkaya & ElMaraghy, 2006** (CS)**, Samy & ElMaraghy, 2012b** (CS) <u>*No of processes*</u>: Sivadasan et al., 2002 (S), **Garbie & Shikdar, 2011a** (CS)**, Garbie & Shikdar, 2011b** (NE), Blecker & Abdelkafi, 2006, **Deshmukh et al., 1998** (NE)**, Jacobs, 2013, Schaffer & Schleich, 2008** (CS) <u>*No of production lines*</u>: **ElMaraghy et al., 2012, Wang et al., 2011, Kuzgunkaya & ElMaraghy, 2006** (CS)**,** Sivadasan et al., 2002 (S)**, Garbie & Shikdar, 2011a** (CS)**, Garbie & Shikdar, 2011b** (NE), Blecker & Abdelkafi, 2006**, Deshmukh et al., 1998** (NE)**, Perona & Miragliotta, 2004** (CS)**, Schaffer & Schleich, 2008** (CS)**,** Hayes & Clark, 1985 <u>*Manufacturing strategy*</u>: **Garbie & Shikdar, 2011b** (NE), Blecker & Abdelkafi, 2006, Wiendahl & Scholtissek, 1994 <u>*Resources*</u>: **Garbie & Shikdar, 2011b** (NE)**, Deshmukh et al., 1998** (NE) <u>*Job shop*</u>: **Deshmukh et al., 1998**) (NE) <u>*Capital costs (rent/heating):*</u> **Perona & Miragliotta, 2004** (CS)

Table 4 - Manage logistics and warehousing

<u>*No of components*</u>
<u>*Transportation and handling within the production site and warehouse*</u>: **ElMaraghy et al., 2014** (CS)**, Garbie & Shikdar, 2011b** (NE)**, Deshmukh et al., 1998** (NE)**, Samy & ElMaraghy, 2012a** (CS) <u>*Product assortment in inventory*</u>: **Thyssen et al., 2006** (CS)**, Jacobs, 2013** <u>*Scrap*</u>: **Perona & Miragliotta, 2004** (CS) <u>*Location of warehouses*</u>: Hayes & Clark, 1985

<u>*No of finished goods*</u>
Product assortment in inventory: **Li, 2007** (NE), Sivadasan et al., 2002 (S), **Perona & Miragliotta, 2004** (CS)**, Jacobs, 2013, Benjaafar et al., 2004**)
Warehouses: **Garbie & Shikdar, 2011a** (CS)
Inventory: **Garbie & Shikdar, 2011a** (CS)**, Perona & Miragliotta, 2004** (CS)**, Foster & Gupta, 1990** (CS)**, Benjaafar et al., 2004, Blecker et al., 2004**
Transportation and handling within the production site and warehouse: **Garbie & Shikdar, 2011b** (NE)**, Deshmukh et al., 1998** (NE)**, Perona & Miragliotta, 2004** (CS)**, Samy & ElMaraghy, 2012a** (CS)
Identification system: **Garbie & Shikdar, 2011b** (NE)
Scrap: **Perona & Miragliotta, 2004** (CS)
Administrative costs: **Rommel et al., 1993** (CS)**,** Wiendahl & Scholtissek, 1994

Table 5 - Markets, customers, and capabilities

No of components
No of orders: **Thyssen et al., 2006** (CS)**, Perona & Miragliotta, 2004** (CS)
Order size: **Perona & Miragliotta, 2004** (CS)**,** Cooper & Kaplan, 1998
No of finished goods
No of orders: Sivadasan et al., 2002 (S), Blecker & Abdelkafi, 2006, **Perona & Miragliotta, 2004** (CS)**, Rathnow, 1993** (CS)**,** Wiendahl & Scholtissek, 1994
Demand: Sivadasan et al., 2002 (S), **Garbie & Shikdar, 2011** (NE)**, Deshmukh et al., 1998** (NE)
Information flow: Sivadasan et al., 2002 (S)
No of customers: **Garbie & Shikdar, 2011a** (CS), **Perona & Miragliotta, 2004** (CS)**, Rathnow, 1993** (CS)
Order size: **Perona & Miragliotta, 2004** (CS)**,** Cooper & Kaplan, 1998
Order taking process: **Blecker et al., 2004**

As it can be seen from the tables above, the main sources of complexity in products are the number of variants and components. These factors indicate aspects of the product that are responsible for increasing complexity in the business processes. Specific process steps identified are the flow of materials, variety in the production lines, machinery, warehouse and distribution, customers' service and order handling process. In detail, batch size, set up time, waiting time, tools and flow shops are the main factors related to production and machinery. With reference to delivery, CCFs identified are number of vendors, lead times and delays. Logistics and warehouses gather also various CCFs, such as number and size of warehouses, locations, capacity, variability of inventory and handling processes in the warehouses. Through these factors complexity costs can be quantified.

It should be mentioned that in the literature review, some of the CCFs are quantified or/and tested in cases. In addition to that, the level of detail, regarding the quantification method and the data required vary significantly among the different articles. However, these two aspects (quantification methods and data acquisition) are not considered in this current work.

Research methodology

This paper examines the existing literature on complexity management, and compares the CCFs identified in the literature review to those identified in case studies. Firstly, the various approaches of analyzing complexity by academia and practitioners are examined and discussed. Then, the factors for quantifying complexity, both from the literature and the case studies, are identified and then categorized. Therefore, an integrated framework, linking complexity in both products and processes is used, and is built upon the industrial standard for process classification, in order to enable classification of the CCFs.

Seven companies have been used as case studies. Each company has been researched for a 5 month period, so that it would be possible to collect and analyze the required data. In all cases, CCFs were identified and evaluated. This in depth analysis allows relatively high validation of the acquired information (Yin, 2003). Then, the CCFs identified in the case-studies are also classified.

The APQC industrial standard is used for that purpose (APQC, 2015). Since this classification framework describes all the processes in an industrial environment, it can be applied to all the companies examined. The purpose of categorizing the CCFs under the APQC framework is to enable a cross-examination and comparison among different manufacturing industries and allow for generalizability of the research method. This categorization also serves a direct comparison between the factors discussed in the literature and those identified in the case-studies.

Case studies

In order to test the suggested methodology and provide empirical evidence, seven companies have been examined as case-studies. All companies are in the manufacturing industry, however they produce different products and they differ in size. The reason for selecting these companies with such diversity is to compare the CCFs across organizations, to get a better understanding in tandem with setting the limitations of this research. The following table describes the main characteristics of the seven companies.

Table 6 - Overview of case-studies

Company	Product	No of employees / size	Production strategy	Number of product variants
A	Medical devices, sensor cassettes	2400	CTO	120
B	Pumps	500	ETO (MTO, CTO)	2736
C	Analytical instruments	1200	CTO	40
D	Commercial vacuum cleaners	5200	CTO	350
E	General Building Insulation products	7800	CTO	175
F	Mattresses	274	CTO	3714
G	Frozen food	1000	-	666

At this point, it should be noted that Company G is not in the manufacturing sector, as it produces frozen food. However, it is included in this study as the main processes, such as logistics and distribution, management of vendors and suppliers, warehouse management, and handling processes are similar to those for companies operating in the manufacturing industry.

As it can be seen from the table above, the companies vary in size and type of products they manufacture. The unit of analysis is the final variants that the companies offer to their customers. In order to ensure consistency among the different cases, all data is obtained from the ERP systems. The data is also discussed with the project managers, so as to certify that the research team has all the information needed and that the data acquired is up-to-date. Moreover, a research protocol is developed and followed in all cases, regarding data retrieval and processing, in order to ensure external validity of the research. The following table provides an overview of the CCFs identified in each case. After each CCF, if identified in a case, brackets with the name of the company follow. When quantified, the name of the company appears in bold.

Table 7 - Categorization of CCFs in the case-studies under APQC standard

Product/ Process	**No of components**	**No of FG**
Plan for and align supply chain resources	No ,State, type of material handling systems | material flow pattern	No, state, type of material handling systems | material flow pattern [D]
Procure materials and services	Location of suppliers | No of suppliers [**G**]	Location of suppliers | No of suppliers [**G**] | Cost of sourced components [**C**,D]
Produce/ Manufacture/ Deliver product	Assembly| tools | No, Type, state of machines| No, type, state of buffers| failure| Production lines| job shop | waiting times | operator [E] | Capacity utilization [**F**] | set up [D] | changeover [E,**F**] |batch size [**E,F,G**] | capital costs (rent/heating) [G]	Assembly| tools | No, Type, state of machines| No, type, state of buffers| failure| no of processes| job shop | operator [E] | capacity utilization [D,**F**] | No of production lines [D] | manufacturing strategy [D] | resources [D,E] | capital costs (rent/heating) [D,E,G] |Indirect production cost [A] |Direct production [A,D] | Overproduction [D]
Manage logistics and warehousing	transportation and handling within the production site and warehouse [**B,**G] | product assortment in inventory [**A,B,C,D,F,G**] | scrap [G] | location of warehouses [D]	warehouses | identification system | product assortment in inventory [**A**,B,**C,D,E,F,G**] | inventory transportation and handling within the production site and warehouse [**A,**D,**E,**G] | scrap [A,**E,**G] | administrative costs [A,**D**] |Freight [**A,D**] | Insurance [**E**] | Shelf-life [G]
Markets, customers, and capabilities	no of orders [**A**] | order size [**A**]	information flow| No of customers | no of orders [**A**] |demand/sales [**A**] | order size[**A**] | order taking process [B,**D,G**]

As it can be seen from the table above, CCFs identified in the case-studies cover the same business processes as from the literature review. The main limitation to this research is the availability and validation of the data acquired. For that reason, the research team was not able to quantify all the CCFs identified.

Discussion and Conclusion

This research focuses on identifying and categorizing CCFs from the literature review and the case-studies under the APQC framework of process classification. Product complexity, measured in terms of number of components and number of finished goods, causes complexity to several process steps. By comparing the results from the literature review and the empirical evidence regarding product complexity, it can be seen that CCFs related to material handling systems have not been identified in the cases, as well as factors related to machines, buffers and tools. On the contrary, in almost all cases have been identified and quantified CCFs in processes related to inventory, production and sales. In detail, CCFs related to the process group of logistics and warehouse, such as freight costs from the warehouse to the distribution centres, insurance costs of finished goods and their shelf-life have been identified and quantified in some of the cases, but not in the literature. This, points out the need of expanding the limits and depth of the literature research.

Factors related to markets and customers have been identified in the cases, yet not quantified. The same applies for material flow, where the lack of data did not enable the research team to quantify the complexity cost.

Summarizing the findings from the literature and the empirical evidence, the most common CCFs discussed in the literature and identified in the case studies are related to the number of components and variants kept in stock, machine utilization, batch sizes and changeover times. Furthermore, processes related to supply, logistics and distribution gather also numerous factors. In detail, transportation and handling within the production site and warehouse, number and size of orders, and number of suppliers are the “usual suspects”.

In overall, it can be seen that the factors discussed in the literature align with the factors identified in the case-studies. Additionally, the use of the APQC framework and the classification of the CCFs allow for cross-examination not only between the literature and the empirical evidence, but also among different companies.

The results indicate that the complexity in products, described by the number of components and finished goods, are the source of increasing complexity in processes, such as production and delivery. This research is a stepping stone in order to develop a concrete framework for managing complexity in the manufacturing sector. Data acquisition and validation, quantification methods and methods for application of the CCFs classification in different industries are future research fields.

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ARTICLE B

Two-way substitution effects on inventory in configure-to-order production systems

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Abstract - **In designing configure-to-order production systems for a growing product variety, companies are challenged with an increased complexity for obtaining high productivity levels and cost-effectiveness. In academia several optimization methods and conceptual frameworks for substituting components, or increasing storage capacity have been proposed. Our study presents a practical framework for quantifying the impact of a two-way substitution at different production stages and its impact on inventory utilization. In a case study we quantify the relation between component substitution, and inventory capacity utilization, while maintaining the production capacity as well as the external product variety.**

Keywords - **Complexity Management, Mass Customization, Inventory Control, Component Substitution**

I. INTRODUCTION

A major challenge many manufacturing companies are facing nowadays is the ability to satisfy more customer needs with a diversified product portfolio, while sustaining a low level of complexity. In order to obtain a competitive advantage, companies have been significantly expanding their product variants, causing an inevitable complexity in product architecture, assembly and supply process [1]. Mass customization offers a promising approach for bridging this gap between efficiently addressing evolving market requirements and offering high product differentiation. Related principles aim to serve this need by providing unique products with a near mass production efficiency. In particular, in a configure-to-order (CTO) production environment the product differentiation can take place on several levels, from modules or sub-assemblies to final assemblies. Yet as companies are trying to fulfill customer demands with higher product variation, product and production complexity increases. This increase in complexity often results in a disproportional distribution of cost throughout the value chain, leading to a significant amount of unprofitable product variants. From a manufacturing perspective, a common way of determining the profitability of each variant is to relate it to the related production flow, in terms of cost for Stock Keeping Units (SKU) [2].

One of the suggested approaches to assess the impact of the increasing product mixes on firm's performance is to investigate how variety complicates the assembly process and supply chain operations [3]. Two factors of increasing complexity are introduced by [4], firstly the number and diversity of features to be manufactured, assembled and tested, and secondly, the number, type and effort of the tasks required to produce the features. Yet traditional production and inventory planning related research has concluded to an integrated model optimizing the values for the process mean, quantity, and production lot size [5]. While both aspects are relevant when investigating the impact of increasing product differentiation, their interrelated impact has seldom been discussed. This research therefore studies how both reducing product portfolio complexity as well as increasing inventory utilization can contribute to the overall performance of manufactures offering custom tailored products.

The remaining paper is structured as follows: after having introduced the research topic, section II discusses the related literature, builds the conceptual framework for the proposed approach and discusses the research aim. Section III substantiates the research methodology, while section IV describes the results from testing the suggested approach on a case study. Finally, a conclusion of the research outcome is given in section V.

II. LITERATURE REVIEW

A. Complexity and Product Architecture

Over the years, numerous studies have been conducted aiming at analyzing and evaluating the complexity that arises from the product range of manufacturing companies. The term itself has been discussed in several contexts. Complexity is defined as "a measure of how product variety can complicate the production process" [6]. In the same concept, [7] points out that complexity is preventing a company from changing its organizational structure, processes and products, and that it is connected to the interrelationships of the system components. Product complexity is quantified by [8] to test the impact of product variety on quality and productivity in a LEAN manufacturing environment. Several researchers have performed similar work [9,10,11], with a focus on measuring how the production process is affected by product complexity caused by increasing number of variations. Product architecture and production strategy are criteria for assessing concepts in product complexity management [12]. Reference [13] investigates the benefits of controlling variety in product architecture on reducing inventory complexity, by moving the customer order decoupling point towards the front-end, i.e. postponement. On the other hand, a widely used approach for measuring systems complexity is typically based on entropy measures [7].

B. Method for ABC differentiation

The ABC analysis was introduced by Pareto [14] and has been further used in operations management context. Products are categorized in A, B, and C products based on the relative distribution of cost and usage of the SKUs. This multiple criteria of ABC product prioritization further considers aspects of inventory management, such as lead time, substitutability and variability [15].

With the rapidly increasing number of variants, manufacturers are trying to maximize the variants they are offering, in order to serve their customers' needs, increase competiveness and identify the market niche. However, not all variants contribute to the net revenue neither at the same percentage. As a result large product variety does not imply for stable long-term profitability [16, 17], and the ABC product differentiation becomes imperative. To overcome this unequal distribution, later studies have investigated the relation between the ABC product differentiation and component substitution [18].

C. Substitution at different stages

Substitution is a method, which complies with mass customization principles and platform designs. Current research has classified two aspects of substitution: controllable firm-driven and uncontrollable customer-driven substation, e.g. cannibalization. Hence, to study the direct effect of substitution, this research is primarily focused on firm-driven substitution at a module level. To this end, cases where the sales representative or even the customer himself decides on the substitution of one final product with another [20] are excluded from the literature review. The primarily focus is on one- or two-way substitution from a production and inventory perspective.

A model is developed by [19] to determine the optimal component quantities in an assembly-to-order system with component substitution, so as to maximize manufacture's profitability.

The Requirements Planning with Substitution (RPS) model has been introduced in order to determine the production quantity of each component and component substitution [21]. The algorithm is based on demand and production quantity, and includes holding and converting costs of components. The component substitutability is composed of flexible Bill-of-Material (BOM) and component commonality. Based on the previous research, an alternative heuristic approach is suggested for make-to-order products, which also includes fixed and variable production costs and facility location [22].

Several other researchers have considered product substitution based on the demand. A model is created by [23] in order to define the lot sizing problem by substituting product variants of low quality with high quality. On the contrary, [18] develops algorithms in order to define the lot size and substitution between two products. The product in lower demand can substitute the product in higher demand, with or without the need for redesign.

D. Research aim

Based on the previous literature review, this paper attempts to contribute to the quantification of the relationships between product complexity and inventory utilization. The factors taken into consideration are product commonality on module level, substitution on component level and inventory capacity. Drawing upon the basic idea of mass customization, we present a concept where the final product variation is not to be decreased and for short and mid-term planning the production facility is considered under the limitation of neither expansion nor change. The ABC categorization approach is used to determine the appropriate components' substitution strategy.

The purpose of this paper is to examine the inventory optimization within a middle-term planning horizon, by adapting the product assortment. Previous research has shown the dependencies between the two aspects; however in this paper we examine those from an alternative perspective, where we use the product mix as a variable, while the operation flow a kept constant. Due to limitations on expanding stock and number of machinery within the given planning horizon, the impact of the product assortment adjustment is used to measure productivity.

Based on the above, the following proposition is formulated:

Proposition 1 (P1): Substitution on a module and component level contributes to improving of the production flow and capacity utilization of inventory.

III. RESEARCH METHODOLOGY

Based on a literature study, the paper first examines the interrelation between the product mix and the production flow in terms of complexity. Mass customization principles are highly related to the dependency between complexity management and profitability optimization [24]. Reference [13] for example suggests analyzing the interrelation between product variety and the process domain. In order to create an understanding of their relative importance within the context of complexity management, a case study of a manufacturer offering CTO products is performed. The data sample includes product orders and the related daily activities in inventory utilization for a one-month period. This in depth analysis follows the proposed methodology, explained in the following sub-sections, and hence allows relatively high validation of the acquired information [25]. The subsequent section describes the suggested approach.

A. ABC product categorization

To categorize the product portfolio, an ABC analysis based on the Pareto theory [14] is performed on component level, where the sales volume of finished products is used to differentiate between the three categories. In detail, 80% of the sales correspond to fewer products, which are considered as A products. Similarly, 15% of the sales volume corresponds to the B products and 5% to the C products.

Sales values are typically stored on a final product level. To be able to perform the ABC categorization on component level, a variance decomposition structure is used, where each finished product is broken into its different components, based on the listed BOM. The sales volume of a finished product indicates its category. Through the variance decomposition analysis, the sales volume of the components is set in relation to the sales volume of the finished product. Next, this variant categorization is used to implement the two-way substitution.

B. Substitution and process flow

The second aim of the research methodology is to implement a substitution method in order to measure the impact on the inventory utilization. The suggested approach is based on the theories discussed in the literature section; in this research a combination of the substitution methods is investigated and a two-way substitution method is proposed.

The first step of this method focuses on utilization of the C component variants kept in stock, in order to increase their utilization and free up the stock capacity. C components have by definition lower sales volume. They are taking up space in the stock for a longer time period than A components, which are used frequently. The quantification of the stock capacity is calculated based on the average number of pallets occupied by each component in stock. Data required for this quantification are the quantity of A, B and C product components and the quantity of each of them per pallet. By dividing those numbers, the average number of pallets per product is calculated. The number of components per pallet varies among the different components due to size differentiation.

According to the suggested method, the C components kept in stock would replace the similar components in the A products. The main challenge is to identify which C variants could substitute the A variants in the final product assembly, without compromising neither the quality nor the specifications of the finished product. This first method can be seen as a suggestion that can be implemented directly, with a focus on achieving immediate impact in inventory capacity.

The second step of the substitution method proposes a short-term solution, to be implemented in the following two years, in which the A components substitute the C components in the final product. This results in out phasing the C components of limited utilization, which in turn leads to an increase of the inventory capacity. At the same time the replacement of C components enables higher stock utilization of A components. The substitution of the C components has positive effects on the inventory capacity, as the slow moving pallets with C components kept in stock are replaced by pallets with A components.

IV. CASE STUDY

In order to test the proposed framework and quantify, the production flow optimization by adapting the product assortment, a case study of a manufacturer in the CTO industry is performed. The company produces plaster gypsum boards for the construction industry. The final product consists of several layers (components): plaster façade (with or without paint), gypsum board, light reinforcement, heat and fire insulation. The challenging aspect of this specific case study is the lack of capacity expanding options, especially on large scale; such as expansion of the production site or the warehouse, purchase of supplementary machinery. As a result, the chosen case study is selected as an example where the optimization of production flow and inventory utilization could only be achieved by the examined proposition. Empirical data were gathered on a daily basis for one-month period, and the forecasted increased demand in the short-term horizon of a two-year time period. The data sample regards all product orders and the related daily activities in machine and inventory utilization. Besides, the data collection includes the modular structure of the products in terms of assembly processes and stock capacity utilization. The two year horizon is considered to be a sufficient period in order to assess the results of the substitution methods, without further investment on machinery and/or expansion of the inventory capacity.

In order to implement and evaluate the suggested approach on this case study, the analysis of the current state is to be used as a baseline. The following table summarizes the data required for the analysis.

TABLE I
RESEARCH PROTOCOL

Data needed	*Quantification*
1. **BOM of finished products** **Sales volume of finished products**	ABC analysis on the component level Substitutability on the component level
2. **Number of pallets with C components in stock** **Number of pallets with A components in stock**	Stock utilization caused by substituting C components with A

Implementing the suggested approach, an ABC analysis was performed on finished products and subsequently on components. The following figure illustrates the relation between the volume of finished products and the number of variants, based on the ABC product differentiation made after the related data set was acquired.

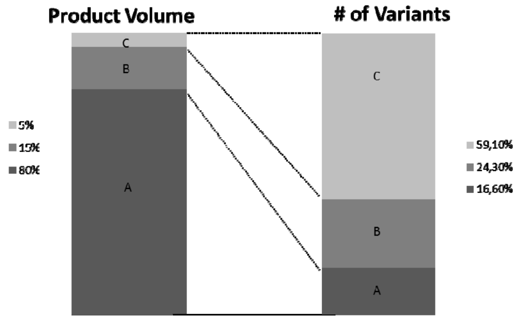

Fig. 1. *Percentage of finished products and of their variants*

The analysis of the current state constitutes the first step of the proposed framework. The historical data on sales volumes helps to estimate the current market trend and indicates in which steps of the production the inventory capacity exceed the maximum level in stock keeping units. The current state is used as a baseline scenario and serves as a comparison when evaluating the alternative solutions. The first scenario suggests substituting C variants with A variants on component level, i.e. at an early stage of the production process. In our case study, the results from the early component variant decrease through substitution lead to a reduction both in stock capacity requirements.

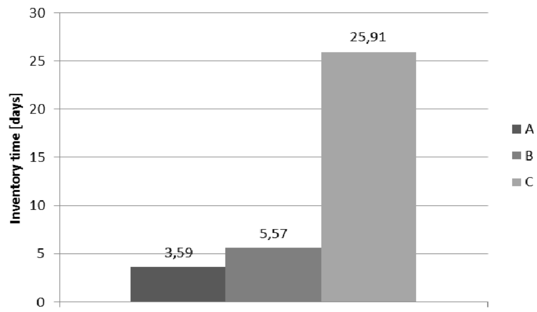

Fig. 2. *Duration of stock keeping per ABC component*

The above figure shows the average time for the A, B, and C components kept in stock. C components have in average 20 times more inventory time than A components. Due to this ratio, by eliminating C components the stock capacity will increase rapidly.

Based on the number of pallets in stock for each component, the following figure clearly illustrates that as low runners, C components require significantly higher capacity. More precisely, C components take overall 43% of the available storage space. By substituting C components with A components, the storage space will become available for A components, which will also lead to increase the production of A components.

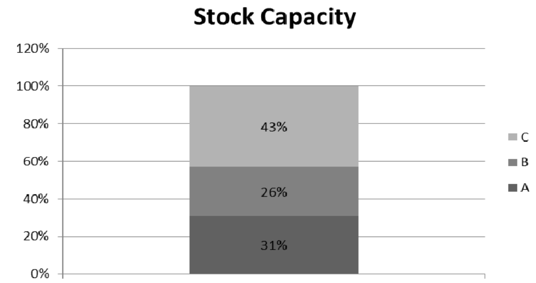

Fig. 3. *Percentage of stock capacity per ABC component*

The second scenario consists of a combined direct and short-term solution, with two-way substitution at a later stage in the production process. The first step suggests the substitution of A variants by C variants, in order to reduce the number of the slow moving C variants in stock. This approach may be applied, as in this case this substitution does not jeopardize the quality of the final assembly. For the case products the only difference between the two variants is the size of components (length, width), maintaining the variation of the final products constant. The second part of this scenario is the short-term suggestion, which introduces substitution of C components on the final products by A ones. This substitution takes place at a later stage of the final assembly. The outcome of this scenario is a great reduction of stock capacity requirements, as the slow moving C variants are no longer produced. This strategy results in freeing up the space occupied by C variants and providing more space for the widely used A variants.

TABLE II
SUMMARY OF SUBSTITUTION STRATEGIES

	C plates for A cores	A plates for C cores	Both strategies
Total variants	618,8	618,8	618,8
Total eligible c plate variants	137,8	24,7	149,5
Total variants %	28,9%	5,2%	31,4%
Total pallets	83,96	14,97	92,70
Total pallets %	10,2%	1,8%	11,3%
Total cost	€ 192.649,05	€ 181.933,90	€ 374.582,95
Cost per pallet	€ 2.982,82	€ 15.796,66	€ 5.252,86

The following figure illustrates the capacity utilization for the components kept in stock.

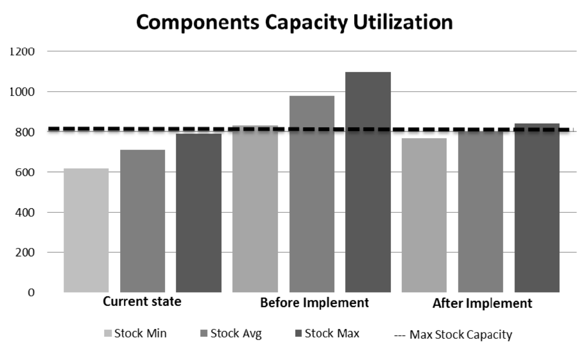

Fig. 4. *Capacity utilization for components*

Finally, three scenarios are compared: the current situation, the future state (in two years) without making any changes and the future state after implementing the suggested approach. The result shows that by substitution of C components with A, the average stock capacity will not exceed the maximum limits.

V. DISCUSSION AND CONCLUSIONS

With mass customization academia has addressed a growing demand for custom tailored products. From a solely mass production environment, manufacturers have been utilizing CTO strategies to realize higher product variety. In designing CTO production systems several considerations are made with regard to component substitution and inventory optimization. One way of balancing the right level of variety throughout production is by managing the complexity of the system.

With this study we have presented a practical framework for reducing the complexity level at different stages in production. An ABC categorization based on sales volumes has been used to distinguish between slow running and fast moving components, while BOM structures of final products have been analyzed to identify the sales volumes components and modules. A two-way substitution has been used on different stages during production and its impact on capacity utilization for storage space has been discussed. The framework was tested on a case study, where a CTO manufacturer has been challenged with an increased customization demand and limited inventory capacity. Based on performed analysis, the impact of a number of complexity reduction scenarios was quantified in relation to total production cost and utilization. Future research may include considerations on lot sizes and machinery utilization.

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Managing Variety in Configure-to-Order Products - An Operational Method -

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Abstract

Companies producing customized products tend to increase the variety of their product portfolio, in order to fulfill the demand of their customers and align their strategies with those of competitors. However, the profitability of product families may vary greatly. The purpose of this paper is to develop an operational method to analyze profitability of Configure-To-Order (CTO) products. The operational method consists of a four-step: analysis of product assortment, profitability analysis on configured products, market and competitor analysis and, product assortment scenarios analysis. The proposed operational method is firstly developed based on both available literature and practitioners experience and subsequently tested on a company that produces CTO products. The results from this application are further discussed and opportunities for further research identified.

Key words: *Configure-To-Order products, operational method, product variety, profitability analysis*

1. INTRODUCTION

The latest tendency in many manufacturing companies is to increase the number of different products they offer to their customers, in order to better satisfy requirements and target new customer segments. Unfortunately, the increment of product variety tends to negatively affect operational performance.

Mass customization has been proposed as an overall approach to offer product variety without penalizing operational performance [1] [2] [3]. However, in order to sustain a competitive price a mass customizer has to keep under control its offering variety [4]. This product variety limitation restricts the need for increasing the information-processing capacity and/or reduces its information-processing requirements thus limiting costs [5]. Therefore, a company that embraces a mass customization approach in order to overcome the trade-off between product variety and operational performance has to decide how to limit its product variety.

One context in which mass customization is adopted is that one of the Configure-To-Order (CTO) operations [1]. When producing CTO products, a desired level of product differentiation can be achieved, as many of the variable parameters can be configured in order to fulfill specific customer requirements. On the other hand, this parameter differentiation enables the production of a vast number of variants, and not all of them contribute positively to a company's profit. As a result, a profitability analysis is of high importance in CTO environments. Several researchers have been working on identifying the value adding product attributes that when differentiated, offer the required variants [6] [7] [8] [9].

To this end, the need of managing product variety has become imperative and several approaches have been applied [10] [11] [12] [13]. However, there is a lack of a structured operational method that incorporates the issues of product profitability and variety in Mass customization and more specifically in CTO environments, in a level of detail that could be of use to both researchers and practitioners. The purpose of this research is to create such an operational method, a detailed approach to how CTO manufactures should deal with product assortment issues, from a strategic point of view. For this reason, several drivers have to be taken into consideration, such as product profitability, customer preferences, and competitive products on the market.

The rest of the paper is structured as follows. Section 2, the literature review, identifies and discusses the existing approaches to profitability analysis studies and the management of product assortment. In section 3, the research operational method is argued. In section 4, the suggested approach is presented, and, then, in section 5, it is tested on a company. Finally, in section 6, conclusions and issues for further investigation are discussed.

2. LITERATURE REVIEW

The literature review is focused on two main research areas, product management and profitability analysis. Nevertheless, early in the review process, it is realized that these two fields are highly interconnected. As discussed in the previous section, due to the nature of CTO products being easily and slightly differentiated, manufacturers should be able to distinguish between the variants that are profitable for a company and determine to what extent they are profitable. For this purpose, the literature review focuses on identifying and discussing the different existing approaches for performing a profitability analysis and determining how the outcome can be used to develop a strategy for managing the product portfolio. In order to gain a deeper understanding and be able to perform a critical literature review, the approaches for profitability analysis are presented first, and, then, the different suggestions for management of a product portfolio are presented.

The literature search has been performed in online libraries by using keywords such as “product assortment”, “profitability analysis”, “product management” and “product planning”. Additionally, the list of references of each article is used to identify related bibliography, as well as the names of the researchers in the recognized research groups within this field. As the content of this research lies also in complexity management, the research group has used sources from an extended literature study performed in this field. The critical literature review is not only used for deeper understanding of the so far developed approaches, but it is also part of the interpretative philosophical position in the chosen operational method [14].

2.1 Profitability analysis

Hansen et al. [15] perform an ABC analysis of product profitability by calculating the contribution margin and net revenue of each variant, and then making the ABC classification by using the Pareto Law [16].

To a broader extent, Wearden [17] lists the main factors that have to be included in a performance analysis. Turnover, profit and ratios, sales records, capital utilization and overheads are among them.

Wheeldon [18] discusses the different aspects that have to be taken into consideration when identifying a product policy. He makes an initial step in connecting the market-oriented factors that influence the profitability of the products and factors that should be considered in developing a product strategy. The local market where a company operates, the international markets of current or future operation and the technological status of both a company’s own products and of those offered by competitors are subjected to further analysis. This will provide the company with a valid perspective regarding its position in the market.

In addition, different methods have also been used by several researchers regarding product profitability, such as mathematical modeling and heuristics. Dobson and Kalish [19] create a mathematical program to quantify the profit of a company, taking into account product desirability and fixed and variable costs. Additionally, the suggested operational method can also include, apart from a company’s own products, similar competitive products. A more customer-oriented ABC analysis is introduced by Juran [20] based on the Pareto Law, and is discussed by Liiv [21] [22], using demand association in order to improve product classification.

These publications have been looking merely into the profitability analysis of products in terms of identifying factors and methods. The rest of the literature review discusses the existing research on portfolio management. However, it also highlights the interconnection between these two areas.

2.2 Portfolio management

By performing a critical literature review, it is realized that portfolio management is highly related to profitability analysis.

Starting from a more general approach, is to point out the need of diversity inputs when developing a product strategy. Muneer and Sharma [23] conclude that production planning, product development, and sales are these aspects.

Flapper et al. [24] discuss two strategies regarding product assortment. The first strategy investigates the contribution of each product to the total net profit, while the second strategy has the same approach but for customers. Two mathematical models are developed for determining the optimal product and customer based assortment.

A similar approach is also discussed by Wheeldon [18]. He suggests that short-term solutions should be oriented towards existing customers when defining a new product range. A framework for evaluation of a product line design is introduced by Li and Azarm [25]. The framework includes factors that affect the evaluation, such as commonality of variants, customer preferences, competitors and business goals. In other words, the framework suggests an internal and external analysis of a company.

The identification of the optimal set of products for a company so as to maximize its value, is also discussed by Gonzalez et al. [26]. Value is realized as the sum of benefits of a set of products minus all costs created throughout product lifecycle activities. This definition of value, and more specifically of the benefits and costs, differs slightly from the economic values used in the ABC classification suggested by Hansen et al. [15].

From a different perspective, De Reyck et al. [27] assess the relation between portfolio management and information technology projects, and identify portfolio performance as one of the objectives. The suggested operational method for financial analysis includes the calculation of return on investment (ROI), internal rate of return (IRR), net present value (NPV) and economical value added (EVA). Similar approaches have been suggested by Benaroch [28] and McGrath and Macmillan [29]. Financial analysis could also be seen as a part of profitability analysis.

A framework for examining the decisions regarding a company’s product variety is presented by Kamalini [2].

The number of products, the targeting markets, and the time for each product to be introduced are identified as the key drivers of variety creation. Its implementation is related to a company's resources and capabilities.

To sum up, the previously discussed literature may vary in terms of methodology and scope. However, this review reveals that there is a common ground to the different approaches regarding portfolio management and product strategy. It has been identified that profitability analysis may be expressed differently, but it is a part of the development of a product strategy. In addition to that, several factors that are taken into consideration in portfolio management have been presented. Sales, customers and competitors are the factors that are met more frequently in the literature. However, in the literature studied no examples were found regarding how to assess the profitability of configurable products including technical assessment of product features, profitability, market aspects, competitors and an internal cost profile.

3. RESEARCH METHOD

The suggested operational method has been built by taking from both the existing literature and some experiences of practitioners. More specifically, the approaches in the field of product management, product planning, and product's profitability have been the starting point for developing the suggested operational method. The operational method is also based on experiences from industry, not only of the members of the research team but also of experts.

The developed operational method has been applied in an actual company. The main aim of this case study has been to test the suggested operational method and receive feedback from the managers in the company. With regards to internal validity, the research team has full access to detailed data from the company. In order to gather accurate quantitative data, un- and semi-structured interviews are performed with the "key" informants. Another benefit for the research group in order to perform this study case is the discussions with the managers throughout the whole period. The managers' expertise was valuable for the analysis performed and for their reflections on the results. The research group had semi-structured interviews with the managers, involved in this project, in order to assess the results and receive feedback. The received feedback is valuable for the verification of the operational method and for further improvements.

4. OPERATIONAL METHOD FOR MANAGING PRODUCT VARIETY

Based on the literature review, an operational method for developing a strategy for product assortment in CTO companies is developed. The suggested framework builds upon the related research fields and attempts to include all aspects that should be taken into consideration in order to develop a strategy for managing product variety.

It consists of four main phases, which have been suggested by product planning literature. The first step is scoping and defining the focus of the products to include in the analysis. The second step is an internal analysis, which is mainly inspired by literature on profitability analysis [15] [30]. The third step is an external analysis, as suggested from the product planning literature. The core idea suggests an analysis of competitors' and their products in order to place the company under investigation in its market position. The final step is a synthesis. Based on the results from the internal and external analysis, suggestions are made for future development. The four steps of the operational method are briefly presented in the following figure and further described in the following sections.

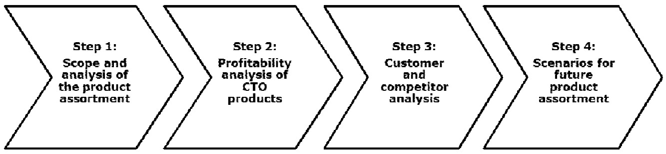

Figure 1. Operational method for managing product variety

4.1 Scope and analysis of the product assortment

The suggested operational method has as its starting point the definition of scoping within a project. Firstly, it has to be clarified which products and/or product families are to be included in the analysis. Based on experience and the literature review on case studies within this area, the main indications for a product to be included in the analysis are low profitability and a decrease in sales volume. These two factors usually signal a need for action and further examination.

Additionally, since the focus is on CTO products, an overview of the technical characteristics of the products is performed. This overview enables better understanding of the product range in terms of structures, components, dimensions, applications, sales price, cost prices etc. The Product Variant Master (PVM) technique is used at this stage to analyze the product structure, including component features, assemblies, and main attributes [1] [31]. An in-depth PVM model gathers almost all data required for the following steps of the discussed framework. Data for this step are to be collected from the designs of the products and the company's internal database, such as Product Lifecycle Management (PLM) [32] and Enterprise Resource Planning (ERP). Un- and semi-structured interviews with persons involved in each project are performed to supplement the accuracy of the findings.

4.2 Profitability analysis of CTO products

Once the analysis of product assortment is performed, the next step refers to the analysis of profitability. Data collection includes sales numbers, cost price, and sales price, which are provided by the company's database [27]. Regarding cost price, it is of great importance to ensure how it is calculated. The most common approach describes that cost price includes material cost and production cost. Additional factors that might add up to the production cost are, as identified from the existing literature, engineering, labor, machinery and inventory costs [33].

Furthermore, an aspect that has to be taken into consideration while performing a product profitability analysis is whether the product is sold as an individual unit or as a sub-assembly. Spare parts are also to be examined separately.

The next task of the second step is to calculate the contribution margins of product assortment. Contribution margin is calculated as follows, sales price minus production cost [34]. As mentioned above and for this case study, production cost includes material and direct labor costs. In some cases it is relevant to include indirect production costs, which could be tools, machines, the rent of a warehouse, and white-collar wages.

Then, a contribution ratio is calculated as the percentage of the contribution margin of revenue. This calculation has to be made on a product- and on a product family- level. The results from this analysis reveal dependencies among the different aspects of the product assortment, indicate the most profitable products, and separate those that contribute on a lower level to the benefits.

4.3 Market, customer and competitor analysis

Step 3 is the analysis of the market, focusing on customers and competitors, in order to understand the placement of products in the market. To perform the customer analysis, information can be gathered on several levels, such as on the level of specific companies, industrial sectors or countries. Data related to customers include sales number, discount policies, and the exact variants that each customer purchases. The last variable is used to define the possible linked revenue of each product. The outcome of this analysis is the classification of the customers and the identification of the interdependencies among the customers and the product assortment [35].

The second phase of step 3 continues with the analysis of competitors [36]. At first, the competing companies have to be identified, and the products they are offering have to be described in a similar way as for the under examination products. This enables a comparison on valid terms. The PVM technique is also suggested at this phase for competitive products. The required level of detail is not as high as it is for the analysis of a company’s own products. This is because the prior interest at this point is to make a comparison among the characteristics that have been identified as main “strengths” and/or “weaknesses” of the own product assortment and of the competitive products. It is realized that due to confidentiality and competitive issues, it is not possible to gather the same amount of information for competitive products. Sales prices and technical characteristics that can be obtained from sales catalogues are of main interest.

An overall conclusion can be drawn by calculating the relative market share for the competitors and the company.

4.4 Scenarios for future product assortment

The final step of the suggested operational method refers to the development of scenarios for a future optimized product assortment [37] [38]. Scenario creation is based upon the outcomes and conclusions of the previous three steps of the analysis.

The scenarios may vary from case to case; however, they are developed based on two main concepts as identified from the literature review namely variety reduction and changes in production flow.

The first scenario refers to decreasing the number of variants [39]. One way that this solution can be implemented is by eliminating the less profitable variants, which have been identified from the second step in the analysis of the profitability of the product assortment [40]; linked revenue and product substitution have to be taken into consideration in the analysis of this scenario. Moreover, the re-designing of specific components, or even products, is another option, which decreases product complexity and manages to maintain the existing variety offered to customers. Re-engineering costs have to be calculated, and the effect of the redesigned products, in terms of materials, dimensions and production process has to be measured based on related aspects, such as freight, inventory and production costs.

Another way of implementing this concept is by complete elimination of the product assortment. This scenario is considered as a drastic solution as it suggests a complete stop of production, in cases where the previous two scenarios do not offer enough benefits to invert the situation of poor performing products. Substitution of obsolete products and linked revenue has to be scrutinized.

The second scenario includes changes in the production flow. Investment in new machinery or new production sequences are the most common suggestions [2] [41]. All the related costs have to be estimated, as well as the depreciation period of any investment.

The final step is completed by an evaluation of the suggested scenarios and the final decision is taken after the comparison of the assessed scenarios that points out the most suitable solution for the development of the future strategy for product assortment.

The suggested operational method discussed in this section is applied to a case study. The description of the case and the results are presented in the following section.

5. CASE STUDY

For the application of the proposed method a CTO company in the heating and ventilation industry is chosen. The company has been operating for approximately 45 years within a global network of more than 40 countries, and its products are designed and produced in Denmark. It employees around 550 persons, and it has an annual turnover of 750 million Danish kroners. In recent years, the company has been facing a decreasing number of sales in the main product family of its portfolio along with declining revenue.

All data used for the analysis and calculations were acquired from the electronic database of the company.

5.1 **Analysis of product assortment**

In the company, the profitability of several groups of products has been discussed for years. In order to focus on and delimit the analysis work, only one of these product groups has been selected. The criteria for selecting this specific group of products is that the overall profitability seems very low and the amount of products in the scope can be analyzed with a reasonable use of resources (in this case, two students working full time for four months and approx. 200 internal hours used by the company). Finally for these products, the company had the data needed for the analysis.

In order to define the scope of this analysis, the research team, along with the managers of the company, first has to consider which products, out of the whole portfolio require further investigation. The examined product family has been characterized by a declining number of sales for the last several years. At this point, the company is considering its options in terms of whether there is profit in maintaining the production or whether discarding the whole family from the product portfolio is a more viable solution.

The product family consists of three products, A, B and C. Product A has the largest size of all, and it is the second most beneficial in terms of net revenue. The market for A is mainly the food industry. Product B contributes the most to net revenue, it has the smallest size and its market is within the industrial sector. Product C is the newest addition to the product portfolio of the company. It has a medium size and low contribution to net revenue. Due to the difference in the material of product C in comparison to A and B, the marine sector is its main market.

The PVM technique is used to a gain technical overview of the product structures and their components.

5.2 **Profitability analysis of configured products**

The first step in the analysis of the profitability of the three products is the annual sales numbers. Data are acquired from the ERP system of the company referring to the last six years. 4.434 orders have been placed for the product family, which resulted in 7.090 units sold. In details, for product A 714 units have been sold and for B 4.912 and for C 1.464.

From the following sales figures, variants that are used as parts of other solutions are excluded; this is due to the fact that the sales price is not registered for each part used but only for the final solution.

The variants taken into account had to meet three criteria: every order has to have an active expected cost price, actual cost price and sales price, in order to have coherency among the data analyzed.

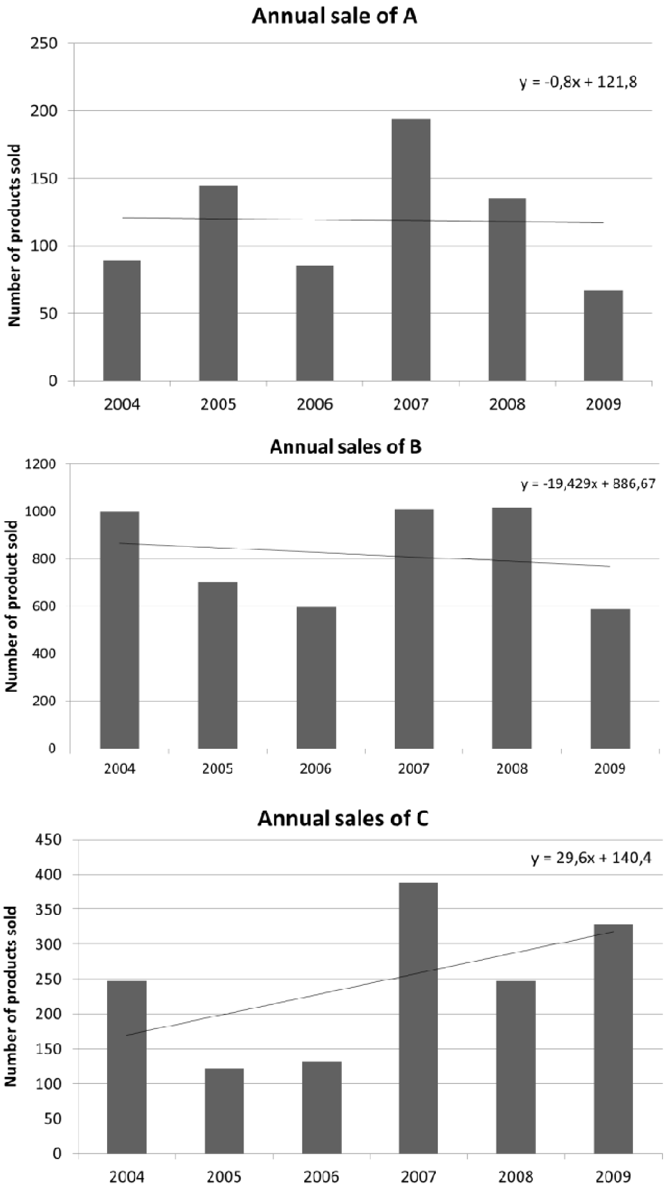

Figure 2. Annual sales of products A,B,C

Data provided by the company include:

- the transaction dates of sales provided in the format month/year, project number
- sale price
- number of units sold
- actual cost
- expected cost
- description of sales
- sale type, indicating if the transaction is a single piece sale or part of other solutions
- country where the sale is carried out.

Spare parts are also excluded from the analysis as there is lack of information about their exact size and the sales country. An analysis is made for each product. The difference between the sale price and the cost price provides the basic contribution margin.

The expected cost price originates from the company's product configurator and is based on bills of material calculation and the cost of labor in the production. The actual cost price comes from the post-calculation at the end of production and includes the same parameters that are used in the previous calculation. The ratio between these two figures gives an indication of whether the configurator is miscalculating a given order or whether there has been some kind of problem in the production.

By performing a Grubb test for the outliers, it is concluded that orders within the range of 65 % and 135 % of the expected cost price are acceptable. The Grubb test detects the outliers and then it expunges them from the dataset. This allows a valid statistical analysis [42].

5.2.1 *Contribution margin calculation*

The contribution margin is calculated as the difference between the sales price and the production cost of each product. Then, the contribution margin is allocated on every different variant. The analysis is made on a product family level and also on an A, B, C product and variant level.

The results indicate that the average contribution ratio for product A is 38,6%. The revenue of product A accounts for 48,1% of the total revenue of the product family and for 44,7% of the total contribution margin. The analysis also reveals that 88,3% of the total revenue comes from 50% of the product range. This raises questions regarding a reduction in the number of variants offered.

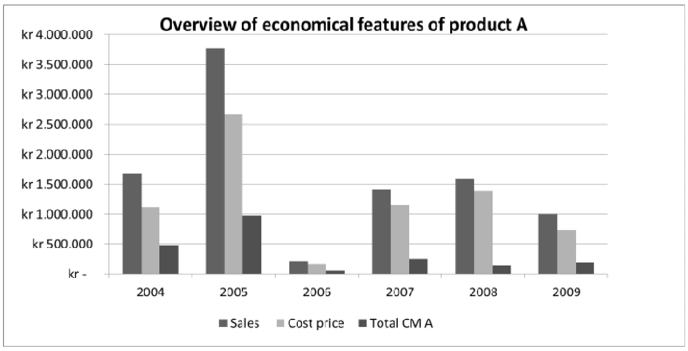

Figure 3. Overview of economical features of product A

Product B, with contribution ratio 48%, is the most profitable product within the family. It also accounts for 35% of the total revenue, 66% of the unit sales and 38,5% of the contribution margin. The analysis, furthermore, reveals that one variant accounts for 25% of the contribution ratio and the number of sales.

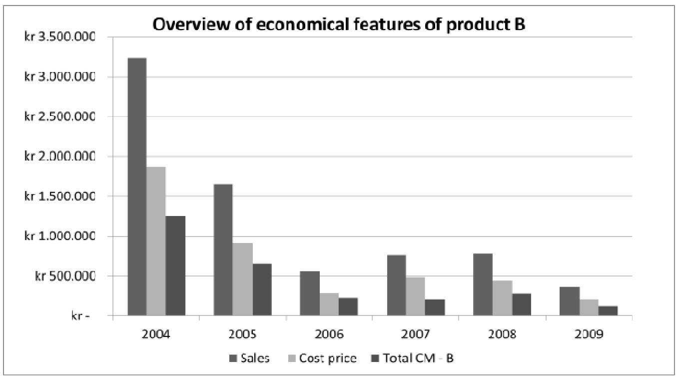

Figure 4. Overview of economical features of product B

The contribution ratio for product C is 37%, which accounts for 18,7% of the total revenue for the product family and only contributes 16,7% of the total contribution margin for the product family. Four variants are responsible for 82% of the revenue. Moreover, the newly introduced product C is not performing according to what was expected from the company, in spite of the fact that it applies the latest technology in product development and strong marketing techniques, which are expected to lead to a significant market share.

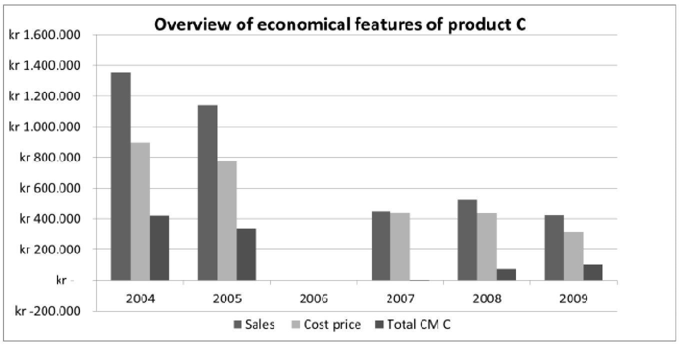

Figure 5. Overview of economical features of product C

Based on the individual sales analysis of each product, the comparison reveals that the most profitable variant identified, is clearly product B.

5.2.2 Engineering Cost

When engineering hours are used, the contribution margin is directly affected because the customer is not charged directly for engineering hours used on a project. The overall cost of engineering from 2004–2009 is 851.877 DKK for known sales. As sales vary through the years, the total cost of engineering during this six years period does not give the right picture of the development for the product family. Therefore, it is more relevant to take a look at the total value of engineering resources used for the product family per year and divide that number by the total sales per year. The result is the average cost of engineering per unit sold, as displayed in the following figure.

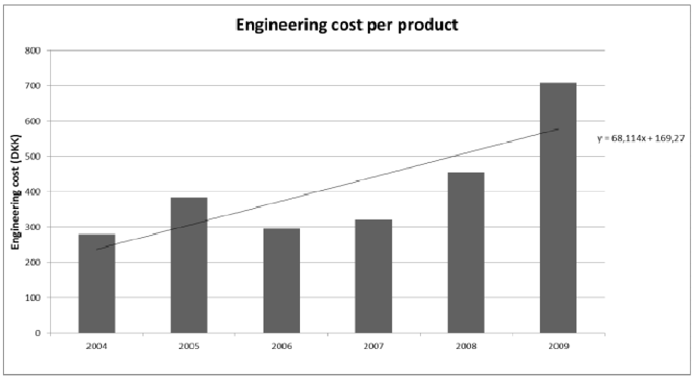

Figure 6.Engineering cost per piece

From these results, it is released that the engineering cost per product is increasing. This increase complements other data that show that the demand in specialized products is increasing through the years.

5.2.3 Sensitivity analysis

A sensitivity analysis is used to investigate the impact of different parameters. In this case study an important parameter to examine is the subsidiary mark-up. The sensitivity analysis explored how much it would mean for the company group in the course of five years if the subsidiary mark-up were 4%, 25 % or 35 %. The results are presented in the following table.

Table 1. Subsidiary mark-up

Year	2009	2008	2007	2006	2005
Sale	983	1400	1594	812	968
4,00%	-85	-895	-448	1306	673
4,51%	-36	-845	-374	1349	741
25,00%	598	-208	555	1920	1619
35,00%	922	118	1020	2223	2068

The negative numbers indicate that the subsidiary is delivering a deficit to the company. In this sense, the positive amounts show how much the company is earning on average on each sold unit. The subsidiary mark-up of 25% is the mark-up claimed by the head of the Netherlands subsidiary, backed up by sales personnel at the company.

5.3 **Analysis of market and competitors**

In this section the results from the competitors and the market analysis are presented.

5.3.1 Competitor analysis

Three main competitors, companies X, Y and Z, have been identified and analyzed. A comparison is made based on the characteristics of the competitive products resulting from the PVM attributes, such as product efficiency and weight, technical characteristics, delivery time and sale price. A part of the analysis is presented in the following table.

The competitor analysis shows that company X is the largest player in the market and has a wide variety of products. Company Y has a smaller turnover compared to the studied company, but the products that company Y mainly focuses on are the ones that are competitive to A, B and C. Efficiency, weight and delivery time are the parameters that the product family under examination lacks. The analysis results in pointing out that the company under investigation is the weakest one in the market. However, the main advantage of the company is flexibility and service, even to the extent of fulfilling customer´s needs even though they do not fit its standard product range.

Table 2. Competitor analysis

Comparison of efficiency and weight between company, X, Y, and Z					
	Static pressure [Pa]	Air flow [m3/s]	Efficiency [%]	Weight without motor [Kg]	Total list-price [Dkk]
A1	2700	10	81	604	105462
Similar product from X	2916	10	79	367	60950
	1808	8	81	461	66292
A2	1880	8	82	578	74773
A3	1880	8	82	718	103494
Similar product from X	1939	8	84	468	62010
Similar product from X	1916	8	82	320	44238
A4	778	21	68	1686	222924
Similar product from X	854	21	72	720	84387
A5	1693	21	74	1154	182811
Similar product from X	1854	21	83	720	102311
C1	516	10	54	187	34012
Similar product from X	369	10	51	320	37067
Similar product from X	467	10	86	720	70696
C2	2879	5	80	187	34012
Similar product from X	2847	5	81	*	29017
C3	3875	1	70	40	10420
Similar product from Y	4000	1	80	*	*
B1	1275	1	71	35	4399
B2	1275	1	75	40	8754
B3	1575	1	75	40	9215
Similar product from X	1430	1	81	27,5	5740
Similar product from X	1693	1	79	27,5	7966
Similar product from Y	1400	1	68	*	*
Similar product from Y	1700	1	52	*	*
C4	1691	8	80	187	34326
Similar product from X	1493	8	80	*	55513
C5	552	1	77	59	10314
C6	570	1	76	102	19751
Similar product from X	609	1	82	41	6823
Similar product from X	577	1	78	50	8951
B4	1421	2	69	98	13305
B5	1421	2	69	102	16238
B6	1421	2	78	121	24134
B7	1308	2	75	59	12329
Similar product from X	1424	2	75,5	34,2	6845
Similar product from X	1443	2	80,9	61	11457
C7	1691	8	80	187	34326
Similar product from X	1716	8	82	320	44238
Similar product from X	1649	8	78	*	35234
B8	921	2	72	89	9580
B9	921	2	72	98	12781
C8	921	2	80	84	14548
C9	880	2	77	102	20811
Similar product from Z	965	2	82,7	67,4	10374
Similar product from Z	967	2	81,4	91	13403
Similar product from Z	962	2	79,6	59	13759
B10	605	8	71	359	37667
B11	605	8	71	394	44713
Similar product from X	579	8	85,1	720	70696
Similar product from X	546	8	75	367	40368
Similar product from X	576	8	85,2	580	48918

5.3.2 Market analysis

The market analysis is performed on a country level and is presented in the following figures for products A, B, and C. Due to a lack of data to establish a coherent customer analysis, this section focuses on assessing market shares.

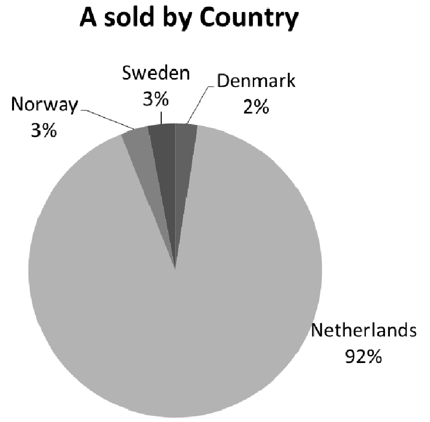

Figure 7. A products sold by country

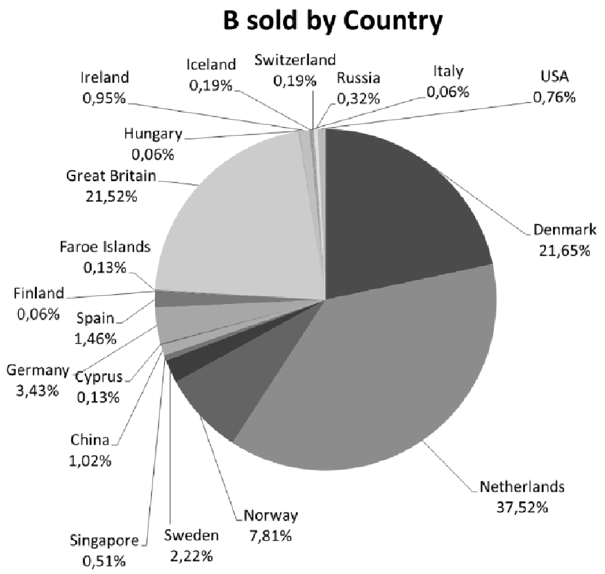

Figure 8. B products sold per country

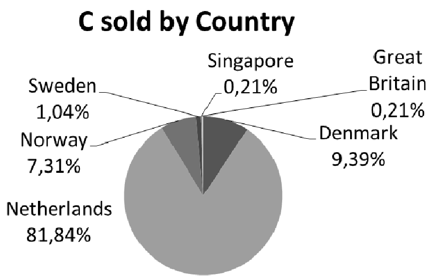

Figure 9.C products sold per country

It has been identified that although all three products are produced in Denmark, the percentage of their sales in Denmark is significantly lower than that in the Netherlands, where the main subsidiary is located.

Finally, the average estimated market share of the company and of its competitors is calculated and illustrated in the following figure. This results in a relatively low market share (1,5%) for the company for heating and ventilation products.

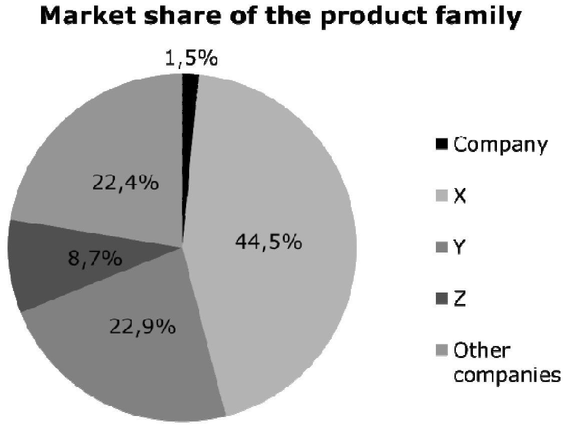

Figure 10. Market share

5.4 Scenarios for future product assortment

Although the product family has been redesigned following the principles of mass customization and standardization, there is a need for re-evaluation and further examination of the production set-up. As has been concluded from the previous two steps of the analysis, the company holds a relatively trivial market share compared to the competitors. In addition, the contribution margins of the three product families have been declining over the past six years. Based on these results, the development of the suggested scenarios focuses on overall cost reduction.

After assessing the results with the company's chief engineer some suggestions can be made. One possibility is to decrease the material use for parts of product A. Another would be standardizing components and decreasing the number of variants.

5.4.1 Decreasing the number of variants

From the PVM, it is identified that the fan is produced in four different positions, 0°, 90°, 180° and 270°. Each position has its own center height for each fan size. It can be seen from the information on the PVM that the center height for positions 90° and 180° is similar, and that positions 0° and 270° are closest to each other. Therefore, it is possible to have the same center heights for positions 90°and 180° and 0°and 270°. This means that the components connecting the fan house to the fan base can be decreased from 4 to 2, which results in decreasing complexity, both production- and assembly-wise.

5.4.2 Investment in a new machine

The plates for the variants produced at the company are cut with a laser cutter. After this operation, the remaining work required is welding. This operation for the product family under investigation is performed manually.

An investment in a robot welder is the second suggested scenario. However, such an investment of approximately 2.5 million DKK, is not affordable for the company. As a result the suggestion includes the robot welder to be used for all the product families produced by the company.

The total number of welding hours spent on manual work is calculated, along with the number of hours that will be saved by using the robot. The estimated annual cost reduction of the implementation of the robot welder is presented in the following table.

Table 3. Cost reduction by implementing the investment scenario

Investment in a new robot	
Initial investment (DKK)	2.500.000
Product family part	16,31%
Estimated cost reduction (DKK)	1.200.000
Investment ratio prod. fam. (DKK)	407.769
Cost reduction (DKK)	
A	51.917
B	31.563
C	37.532
Total cost reduction (DKK)	109.370

Based on the calculations the robot will be occupied for 16,31% of its time by the product family while the rest of the time will be used for the welding process of the other product families of the company. It can be seen from the table that the total cost reduction is not significant compared to the initial investment.

5.4.3 Stop the production

This scenario examines the benefits of stopping the production of the product family. There are two different options for the company in this case, either to sell the customer base or source similar products from competitors.
For the first option, it is required to estimate the future sales and sale values in order to calculate if this is an attractive solution for the possible buyers. This results in 1,25 million DKK earnings in the time horizon of five years for the potential customer. The following table summarizes the estimated earnings for the company when implementing the scenario of base selling.

Table 4. Company's side of NPV with sale with calculation rate of 11%

Year	Income (DKK)	Sales (DKK)		**NPV (DKK)**
0		4.741.300	4.741.300	**7.090.594**
1	521.543		521.543	
2	578.913		578.913	
3	642.593		642.593	
4	713.278		713.278	
5	791.739		791.739	

In order to explore and evaluate the second option, of outsourcing the product family, a comparison is made between the total cost of producing the products in-house, and the selling price for the competitors' products. Outsourcing is 19,2 % more costly for the company than producing its own products (73.301.165 DKK versus 61.479.904 DKK).

5.5 The final decision

The previous steps allowed the company to become ready to take a decision for the future product assortment. First, the product family has been analyzed, in terms of technical characteristics and profitability. Then, an analysis of the customers and the competitors has been performed in order to place the company in its market position. Finally, three scenarios have been created and benefits and costs of each scenario have been quantified.
At that point, the suggested scenarios are presented to the company as recommendations for the future product assortment strategy. Based on the results of the scenarios and the feedback received, after the scenarios have been presented to a workshop in the company, the most feasible solution is to stop the production. If the company decides on outsourcing the variants from the competitors, it would only increase the contribution margin if the company can get a discount on the products they purchase from competitors of at least 16%, based on the cost calculations. As a result, the most profitable solution was to sell the customers' base, which increases the company's income directly.

6. DISCUSSION AND FUTURE RESEARCH

The purpose of this paper is to build and test the suggested operational method for developing a product assortment strategy. Firstly, the relevant theories are used to build the conceptual framework of this research. The four step operational method attempts to guide a systematic approach of product scoping, profitability analysis for CTO products, customers and competitor analysis and scenario creation for future product assortment. It is a tool for assisting and coordinating the decision-making process of the product strategy in a company.
This work intents to contribute to the development of a structured and detailed approach to assessing the profitability of configurable products, including both economic and technical features of products, market aspects and competitors.
The application of the operational method to the case study reveals several options for the company's future and also valuable feedback for further research and extension of the research method. The applicability of both the operational method is tested and verified. Moreover, the challenges in data gathering have been identified. To this end, further research needs to be made in order to establish more explicit criteria for identifying and scoping potential product groups to analyze and to assess the suggested scenarios. Further research needs to done on how to assess the profitability of configured products based on configured modules with varying costs and variant sales prices for the final configured products.
Even though the studied case is considered to be highly representative of the CTO manufacturing context, the main limitation to the present test of the proposed

operational method is its generalizability. As there are results only from one case study, external validity can be challenged [43]. However, this case is considered to be an exploratory study in order to have an initial result from the application of the suggested operational method. Therefore, more cases have to be added to bring the present research further. This will enable not only identify possible additional limitations of the operational method, but also to improve and strengthen the structured approach.

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Upravljanje varijantnošću proizvoda konfigurisanih prema narudžbini – operaciona metoda

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Primljen (25.08.2014.); Recenziran (19.10.2014.); Prihvaćen (20.11.2014.)

Rezime

Kompanije koje proizvode kastomizovane proizvode teže da povećaju varijantnost svog proizvodnog programa u cilju ispunjavanja zahteva kupaca i usklade svoje strategije sa strategijama konkurencije. Međutim, profitabilnost proizvodnih familija može veoma varirati. Svrha ovog rada je da se razvije operaciona metoda za analizu profitabilnosti proizvoda konfigurisanih prema narudžbini kupaca. Operaciona metoda se sastoji iz četiri koraka: analiza asortimana proizvoda, analiza profitabilnosti konfigurisanih proizvoda, analiza tržišta i konkurenata i analiza scenarija asortimana proizvoda. Predloženi operaciona metoda je prvo razvijena na osnovu dostupne literature i iskustava u praksi, a zatim testirana u kompaniji koja proizvodi proizvode konfigurisane prema narudžbini kupaca. Rezultati iz ove analize su dalje diskutovani, a mogućnosti za dalja istraživanja identifikovane.

Ključne reči: *proizvodi konfigurisani prema narudžbini, operaciona metoda, varijantnost proizvoda, analiza profitabilnosti.*

ARTICLE D

Reconfiguring variety, profitability and postponement for product customization with global supply chains

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Keywords: Product customization, Supply chain complexity, Variant profitability, Postponement, Substitution

Abstract. At present, many industrial companies offering high product variety focus on systematically reducing the complexity of their product range and business processes. Related challenges are often named to increase time to market, reduce the effectiveness in product development, and lower process efficiency. For manufacturers with global supply chains additional uncertainties arise in defining the right manufacturing strategy with respect to production location and postponement. To better understand related managerial implications, this paper discusses a case study a global manufacturer providing customized industrial applications. In particular, the study investigates the relationships between product variant profitability and manufacturing strategy relative to postponement and location. The results indicate that an improved configuration of these factors through substitution and supply chain redesign significantly increases the overall product portfolio profitability.

1 Introduction

With the emerging area of mass customization, researchers and practitioners alike have acknowledged a growing trend towards higher product variety and customization. Customizing a product can be described as the process of configuring a product variant by selecting pre-designed components within a selected scope of offered variety [1]. Companies employ customization as a means to differentiate from their competitors by providing unique customer value [2]. Although many positive commercial advantages can be named from offering extensive customization [3], recently a stronger focus has been laid on the downside of the added supply chain complexity [4]. Higher product mixes created through diverse manufacturing strategies have been identified as major complexity drivers throughout value chains [5], often leading to reduced operational performances, such as longer lead times, poorer quality and increased costs [6], [7]. Hence, integrating approaches to complexity management into the framework of supply chain management (SCM) has become compulsory [8].
A major concern in SCM is to systematically and strategically coordinate material flows across companies with the objective of reducing cost and achieving competitive advantages [9]. To account for the immanent complexity from customization, the scope

adfa, p. 1, 2011.

of SCM needs to be aligned with aspects of variant management and postponement, i.e. the degree to which customization is provided throughout the supply chain [10], [11]. This paper adds to the existing knowledge of how supply chains dealing with varying degree of customization can handle the arising complexity. Based on a literature study on designing and managing supply chain networks for customization (Section 2), Section 3 introduces a suggested approach for the reconfiguration of the network design. Next, a case study is presented in Section 4, where empirical evidence is provided on how postponement and substation may positively reduce complexity and simultaneously increase companies´ overall profitability and operational performance.

2 Literature review

2.1 Product customization with global supply chain networks

To compete on international markets, manufacturing companies are organizing their business processes around a global supply chain network [12]. Fig. 1 displays a conceptual model of a hypothetical supply chain network design. From a high-level perspective, supply chains may typically include activities related to engineering and purchasing, manufacturing, assembly, distribution and sales. To serve the needs of local markets, traditionally these activities have in their simplest form been stablished within the country of origin. With globalization firms have over time been moving towards international markets, for which some of the supply chain requires to be outsourced or physically displayed [13]. As indicated in Fig. 1, depending on the sales strategy, to secure lead times and product delivery, sales may for example be displaced to target markets, thereby establishing local sales channels. To lower product costs or to focus on key competences, manufacturing on the other hand may be outsourced or displaced to low cost countries, keeping the final assembly of components in the country of origin [14]. An example of this approach can be seen in the apparel industry, where products are designed in the country of origin, often manufactured in others, and sold locally within target markets [15]. In more general terms, the relative cost advantage of low cost countries and the small value added to the final products is often named to be the main motivation for emphasizing this particular part of the supply chain, like manufacturing [16]. To this end, several studies have investigated the possible gains and motivation from reconfiguring supply chain networks. While major part of the research suggests an overall positive effect on the firms performance, few studies also point out the potential risks with this strategy [17].

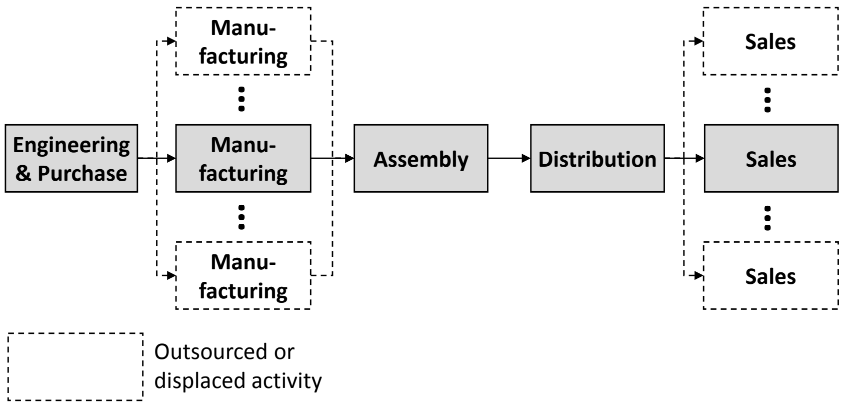

Fig. 1. Conceptual global supply chain network with outsourced or displayed manufacturing and sales

In addition to the network design of a particular supply chain, offering product customization requires consideration about the product design and production planning and control system. The degree to which customization is provided can vary across the entire product portfolio of a company and is often described through the relative involvement of customers with the companies' supply chain, i.e. to the customer order decoupling point (CODP) [18]. As displayed in Fig. 2, the more supply chain activities are directly related to a particular customer order, the higher is the degree of the offered variety and the early in the supply chain the CODP is placed. Literature names a few distinct product planning and control systems allowing for customization, depending on the relative placement of the CODP [19]. In an Engineer-to-Order (ETO) situation, components have to be engineered based on a specific request from customers, forcing all subsequent activities to be directly engaged in fulfilling the order. Due to the early customer involvement, typically ETO products obtain a large amount of variety, but their production volumes are low [20]. In a Make-to-Order (MTO) scenario, pre-designed and available components are used for manufacturing and subsequent assembly of the product variants. In case both engineering and manufacturing activities are performed based on forecast, sub-assemblies from stock are used in the assembly process to Assemble-to-Order (ATO) the requested product variant. To account for a high amount of final variety, a modular product design has been reported to facilitate the separation between manufacturing of components and (final) assembly [21]. With the so called modular product architecture, components or modules can to be produced or outsourced based on forecast and recombined according to the requirements of the customer [22]. This would allow the company to postpone the CODP closer towards the customer, i.e. to a MTO or ATO situation. The so called Type-III postponement strategy aims at capitalizing on standardization and modularity, thereby achieving economies of scale [23].

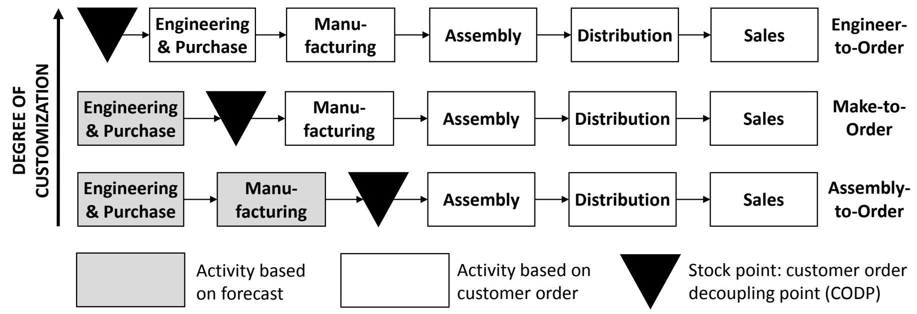

Fig. 2. Degree of customization and placement of the CODP

2.2 Supply chain performance and reconfiguration

Despite the rather simplistic view on the production process, dividing the different production planning and control systems according to the placement of the CODP helps to define clear strategies for a particular supply chain network design. Decisions about a suitable configuration of the network may be related to key operational performance measures of a company, such as to cost and time [24]. From customers perspective, higher degree of customization allows for more engagement in the supply chain and hence to more unique product designs. However, since more activities have to be performed after a specific order has been placed, there is a tradeoff between the uniqueness of the product design and the related delivery time and cost. In general, the higher the number of activities performed for a customer, the bigger the sum of the individual lead times of each process [2]. Moreover, unique designs with higher engineering engagement have often proved to be more costly and less quality assured [25]. Since a higher percentage of the supply chain is performed based on a distinctive customer requirement, processes are less standardized and may involve ad hoc and unproven tasks which require stronger coordination effort [20]. On the other hand, with an MTO and ATO strategy, the increased standardization of components and processes combined with reduced delivery times has shown to be particularly useful for products with moderate or limited variety and high volumes [18]. Therefore, setting the right strategy for the production planning and control system can have a wide-ranging impact on the profitability of the provided portfolio.

Traditionally, decisions about the placement of the CODP are made based on inventory management theories and may include aspects of inventory cost, lead time requirements towards the market, sales volume and order frequency, and scope of offered variety [26], [27]. Accordingly, items with low volumes and high variety should be organized around an early placement of the CODP and vice versa. Recent literature however emphasizes that more and diverse customization significantly increases supply chain complexity, making cost allocation and prices estimations less accurate [8]. Planning with higher product variety often leads to overestimated profits, where the complexity-induced cost of the supply chain are not taken appropriately into account by traditional accounting methods [28]. Schuh et al. (2008) discuss complexity from two forces [29]. External complexity occurs due to desired customer requirements. This defines the number of the offered product variety. Internal complexity describes the processes, parts and product designs across supply chain needed to provide the demanded product variety. Reducing the internal complexity as much as possible by obtaining the necessary external complexity is seen as a guiding principle for managing the complexity across supply chains [1].

A common way to identify unnecessary external complexity is to investigate the realized contribution margins (CMs) for each variant according to the pareto principle [30]. As studies have shown, in complex supply chains a large amount of the sold variants do not contribute if at all to the turnover of firms. Instead, a major part of the turnover is generated from a small amount of the variety [31]. In order to classify which variants to keep and which to reduce or replace, a categorization into A, B, and C products is typically performed [32]. Once unprofitable variants are identified, various initiatives can be enforced to reduce the related complexity. Depending on the product design and the supply chain network, such initiatives may include the increase of modularity [33], postponement [11], or product standardization through increasing component commonality [34].

Yet, due to the rather sensitive operational data, empirical based research considering both analysis on margins and the related initiatives is rare. Hence, the main focus of this research is to find empirical evidence on how to identify the most profitable product variety for product customization regarding production strategy and supply chain set up. In particular this research attempts to answer the following research question:

RQ1: How can the operational and financial performance of a supply chain network for customized products be improved?

This research question is answered based on the three sub questions:

RQ1.1: How can customized products be categorized relative to their degree of customization?

RQ1.2: How can the potential for a postponement of the CODP and a standardization strategy be identified?

RQ1.3: How can postponement and standardization effects on costs and contributions margins be quantified?

3 Suggested approach

As stated in the previous sections, complexity creates uneven cost distribution across the different product variants. Based on the literature, moving the CODP towards the front-end is an effective approach to complexity cost reduction. However, in cases where the manufacturer produces not only ATO products, but also MTO and ETO, the setup varies a lot among the different production strategies. On top of that, the profita-

bility assessment may be calculated through several approaches. Recent literature suggests that in order to have a clear picture of the “high runners” and the “long tail” both CM and sales volume have to be taken into consideration in the profitability analysis.
In alignment with related contributions, this research suggests an approach for profitability analysis and complexity reduction, which can be applied to manufacturing companies with different production strategies. In order to analyze the profitability, an ABC product categorization is performed. Each product is grouped into A, B or C based on its CM and net revenue (NR), which enables the consideration of the sales volume for each variant. To reduce the supply chain complexity, two coordinated methods are considered. The first one relates to postponement of the CODP and the resulting product standardization. Besides, complexity reduction theory suggests the development of modular products that consist of standard sub-assemblies. In that way when an order is placed by the customer, the final configuration of the product can takes place with an MTO or ATO approach. This strategy reduces lead time, complexity cost and production cost. The second method discusses the provided variety of the product portfolio in terms of cannibalization and profitability. Related literature highlights that the increasing variety offered to the customers does not necessarily indicate that a wider range of application is covered. In order to ensure that variants with different production cost and sales volumes are not offered with similar properties and applications, product merging through substitution is suggested. This is done by analyzing the bill of materials (BOMs) and the CMs of these variants.

4 Case study

4.1 Data collection

The suggested methodology is applied on a case study of a Danish manufacturer of pumps. The company produces standardized as well as more specialized products with an ATO, MTO or ETO strategy. The main market requirements for pumps are reliability, functionality, design, price, delivery performance and solution flexibility. The product portfolio of the company includes pumps for chemical, environmental, heavy and petrochemical duty and for general purpose. The data collection is performed through the company’s internal database and includes BOMs, total cost, NR, sales volume, production strategy, and country of production and distribution, on finished good level. The sample size refers to sales within a two-year period (2012, 2013). Semi-structured interviews with project managers are performed, in order to verify the accuracy of the data acquisition.
As suggested in literature, since part of the supply chain is based on forecast, the ATO products have relatively shorter lead times and better delivery performances. MTO products are produced based on an order received from the distribution center. They consist of standard parts, which additionally require special treatment, and are produced in low runs. Before their components can be produced, BOM and prices have to be verified, which results in longer lead times compared to the ATO variants. Special customer requirements are treated as ETO products and hence obtain longer lead times and

higher cost in comparison to the ATO and MTO products. A significant difference between an MTO and an ETO product is that for the latter a dedicated production set-up is required, which involves alternative processes and tooling. Moreover, the R&D department is also involved in the enquiry and quotation process, to verify the feasibility of the customer's requirements and to ensure the supply chain capabilities.
The company acquires two production sites, one in Denmark and one in China, and three distribution centers (DCs), one in each of the following countries: Denmark, China and the USA. The DCs in China and Denmark deliver products produced to the respective site; the North America market is supplied by either China or Denmark. However, the products distributed in Denmark are produced in two ways; either they are entirely produced in Denmark (local), or they are produced as standard semi-finished units (SFU) in China and then the final configuration and testing is performed in Denmark.

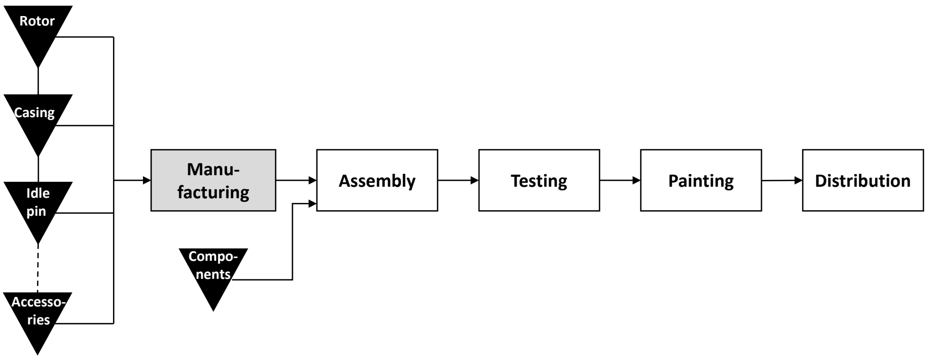

Fig. 3. Local production in Denmark

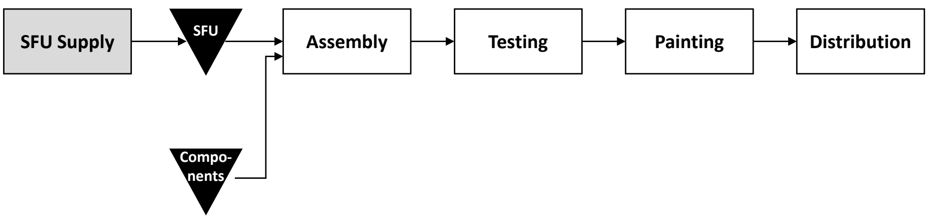

Fig. 4. SFU production in China and final configuration in Denmark

The sample size focuses on one representative product family consisting of 299 variants, the heavy duty (HD) pumps consisting of a modular product architecture. The particular product family is selected due to its significant share of the total sales, which accounts for 60,61% of the total revenue. Moreover, HD pumps are offered based on all three production strategies with a distribution of 32%, 33% and 34% between ATO, MTO and ETO accordingly. To limit the scope of analysis, the sample size refers to products being sold from the DC in Denmark.

4.2 Analysis and results

Currently, the company categorizes the products as A, B and C based on their inventory turnover and their picking frequency. The results from this internal ABC analysis are presented in the following table.

Table 1. Internal ABC analysis

Inventory Turnover	Picking Frequency			
	Category	**A (>20)**	**B (4-20)**	**C (0-3)**
	A (≥3)	18	2	0
	B (2)	11	24	5
	C (0-1)	3	46	190

The ABC categorization is based on internal experience. Products are categorized as A if they have inventory turnover higher than or equal to three and picking frequency higher than or equal to 20. B products are indicated by inventory turnover equal to two and picking frequency between three and 20. Finally, C products have inventory turnover less or equal to one and picking frequency less or equal to three. All the data refers to a 12-month period.

Both parameters, inventory turnover and picking frequency, are related to the sales volume of the products. However, with this internal categorization approach none of the measures accounts for the CM of the products. Yet according to the literature, in order to draw conclusions regarding the profitability of a product, the NR and production cost have to be taken into consideration. This results in questioning the accuracy of the internal ABC product categorization.

By implementing the suggested methodology, an ABC analysis is performed, which categorizes the products based on the NR and CM instead. The CM is calculated as the difference of the NR from the direct production cost, where direct production cost include the cost of material and labor. The following table presents the results of the ABC analysis.

Table 2. ABC product categorization based on CM and NR

NR	CM			
	Category	**A**	**B**	**C**
	A	38	23	11
	B	0	7	88
	C	0	0	132

When comparing the results from the two ABC analyses, it can be concluded that in the company's perspective many C products are kept in stock (81,6%), which leads to increasing inventory costs and consequently complexity costs. From the suggested ABC analysis the ratio of C products is relatively lower (77,3%). Yet the distribution of products varies between the two analyses, indicating that further research is required to identify the cause of this divergence.

To gain better understanding of how postponement may be applied, the results are displayed in relation to the three production strategies (ATO, MTO, ETO). In other words, the products are categorized into A, B or C, based on their NR and CM, revealing a significant difference between how the type of products that are included under each production strategy.

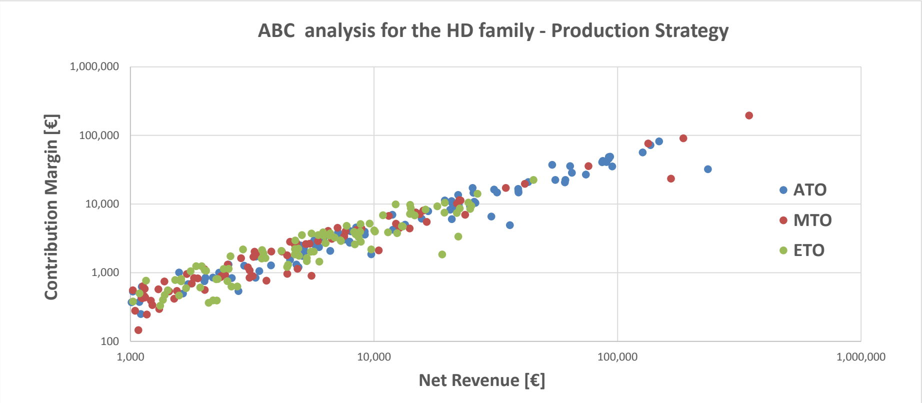

Fig. 5. ABC product categorization by production strategy

As displayed in Fig. 5 above, 60% of the ATO products are categorized as C products. 29% of the ATO variants are categorized as A, and the remaining 11% as B products. However, this result highly contradicts to the internal categorization of a product ATO. ATO products are standardized, produced in large batches and are high runners. That implies that ATO products have lower production cost and higher revenue, which would result in higher CM and, consequently, in an A product. Less contradictory, only 8% of the MTO belong to A and 87% to C products. Finally, as expected only 2% of the ETO products are A and 88% C.

In detail, the following table presents the total cost, net revenue, CM, number of variants and sales volume per production strategy.

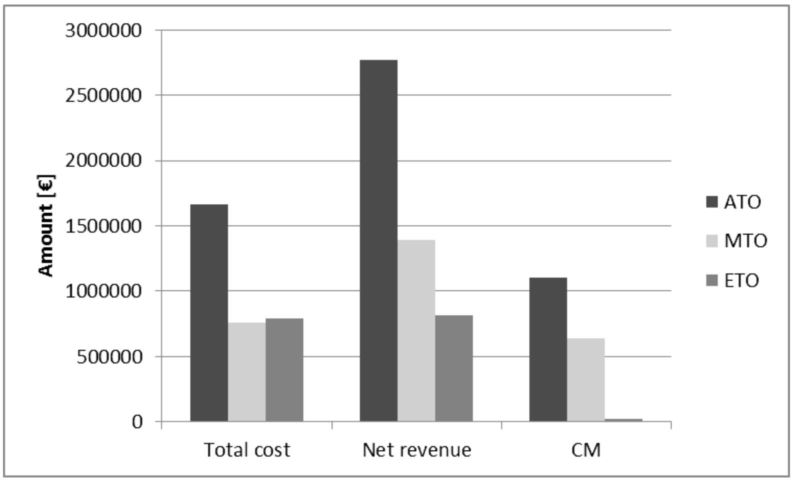

Fig. 6. Comparison of the financial data from the three production strategies

The results from Fig. 6 indicate that the ATO products are more profitable, contribute far more to the company's profitability and are sold in higher volume. However, this again does not conforms with the result from the internal ABC analysis (see Table 1), which shows that 60% of the ATO products are C. Based on the above, a re-categorization of the products under the three production strategies is recommended.

By following the suggested research method, two approaches are implemented. The first one aims at increasing the standardization of the ATO products. The company, as discussed above, uses SFU manufactured in China as pre-assemblies for the ATO products. The products including these SFU have significantly lower production cost. However out of the 97 ATO variants, only in 8% of the cases outsourcing through SFU's is used. The following Table 3 gathers the relevant financial data for the products produced in China and in Denmark.

Table 3. ATO products

Production country		Cost	NR	CM	# of variants	Sales volume
CH	sum	€ 8.826	€ 14.269	€ 5.444	8	273
	aver	€ 1.103	€ 1.784	€ 680	-	-
DK	sum	€ 109.347	€ 194.853	€ 85.505	89	1264
	aver	€ 1.229	€ 2.189	€ 961	-	-

To identify the potential for outsourcing, products with similar properties and sizes produced in Denmark and China are investigated. By increasing the number of SFUs used in the final assemblies, the overall number of variants produced is significantly reduced, thereby decreasing the complexity of the supply chain. The following Table 4 illustrates the results of those calculations.

Table 4. Financial data after implementing the SFU standardization

	Before	After	Difference
CM	€ 3.370.800	€ 3.388.987	€ 18.187
Revenue	€ 6.436.071	€ 6.076.030	€ -360.041
Cost	€ 3.065.271	€ 2.687.043	€ -378.228

For further product standardization, a re-categorization of the products among the three production strategies (ATO, MTO, ETO) is examined. Products with same sizes are analyzed based to their production strategy with the intention to move as many products as possible to the ATO category. Decisions are made after comparing the BOM and the functional properties of the products. This analysis results in increasing the standardization of 36 products, or 12% or the portfolio. In detail, 18 MTO and 18 ETO products are moved to ATO category. The financial impact is illustrated in the following figure.

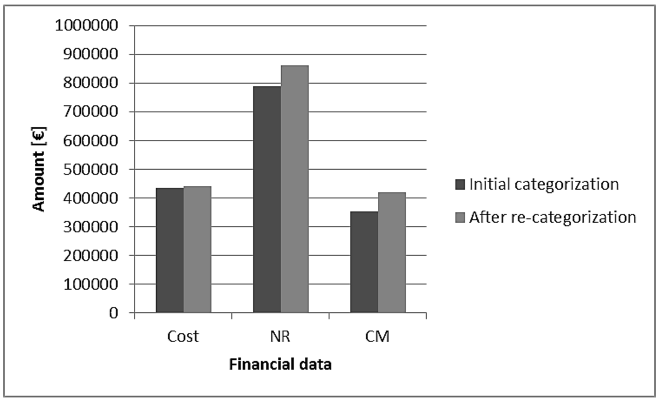

Fig. 7. Comparison of financial analysis of the production strategy categorization

Summarizing the results from the two standardization methods discussed above, it can be seen that the total cost of the HD family is decreased by 4,3% . The impact of the implementation on the NR is not significant, due to the lower sales price the standardized products have compared to the customized ones. Yet, the increase in the CM by 18% (from 354.299 € to 419.314 €) indicates that the profitability of the new product portfolio has been positively affected.

Table 5. Total impact on the HD family

	Before	After	Total Impact
Total Revenue	€ 4.977.942	€ 4.996.389	0,4%

Total Cost	€ 3.212.839	€ 3.074.773	-4,30%
Total CM	€ 1.765.103	€ 1.921.616	8,9%

Next, the potential for substitution is being investigated. The analysis is made in 10 groups of products that have the same size. In particular 98 product variants are merged into 44, where 20 out of them are merged into 13 products that have SFUs produced in China as pre-assemblies. By merging the products, 54 variants can be eliminated, which additionally reinforces the standardization of the product family.

In order to estimate the total effect on the company's profitability after implementing the suggested method of both product standardization and variant substitution, a sensitivity analysis is performed. The following table describes the 4 combinations that are used in order to gain a better understanding of the impact of the approach on the CM of the product family.

Table 6. Sensitivity analysis with 4 scenarios

	A	**B**	**C**	**D**
Cost	-20%	-20%	-20%	-30%
Sales price	0%	-5%	-5%	-10%
Sales volume	5%	10%	0%	20%

For each of the above scenarios the cost, NR and CM are calculated. The results are as follows:

Table 7. Impact of the 4 scenarios

	1	**2**	**3**	**4**
Cost	- 3 %	- 2 %	- 4,1 %	-0,8 %
NR	1,8 %	1,7 %	-1,2 %	1,5 %
CM	10,5%	8,3 %	9,9 %	5,1 %

The negative percentages indicate that there is a reduction after the implementation of the suggested approaches. The results demonstrate that the CM is increased in every case. It worth mentioning that even in scenario 4, where there is no increase in the sales volume, the CM is increased considerably. As a result, the outcome of the sensitivity analysis indicates that the application of the suggested methods for product standardization and variant elimination have an impact on reduction of complexity costs and increase profitability.

5 Conclusion

This research examined the effect of postponement and product substitution on profitability and complexity reduction in the manufacturing industry. The suggested methodology was developed based on recent research studies and is further supported by empirical evidence. A particular pump manufacturer considered being highly representative for this research was used as a case study, due to its diverse production strategy with different degrees of customization and a global supply chain network. The case study investigated variants profitability and identified the realized degree of customization of a selected product range.

The results indicated that there is a significant improvement of the product's profitability once the standardization and substitution method is applied. By managing the existing variety of the product portfolio, eliminating the variants that add no value and/or no additional properties, and postponing the CODP, the operation performance in terms of profitability and lead time was improved. An 18% increase in the CM of the ATO products was achieved by standardizing 12% of the variants. Furthermore, additional effects were estimated from a subsequent variant substitution.

Despite being one of the rare empirical-based studies within this research field, since the results are supported by a single case study, the main limitation to this research is the generalizability. This provides opportunity for further research which would help to investigate the impact of the suggested approach on the different cost elements and complexity costs across a number of cases. Likewise, the distribution of complexity costs over the product range and the effect of the portfolio standardization and substitution are to be further examined. Here, additional case studies may to allow the generalization of the suggested method and further enhance the external validity of the results.

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ARTICLE E

Impact on cost accuracy and profitability from implementing product configuration system – A case-study

Anna Myrodia and **Katrin Kristjansdottir** and **Lars Hvam**

Abstract. This article aims at analyzing the impacts from implementing a product configuration system (PCS) on company's profitability and improved cost estimations in the sales phase. Companies that have implemented PCSs have achieved substantial benefits in terms of being more in control of their product assortment, making the right decisions in the sales phase and increasing sales of optimal products. Those benefits should have a direct impact on improved profitability in terms of increased contribution ratios and more accurate cost estimations used to determine the price in the budgetary quotations. As the literature describes, there are various benefits from implementing a PCS, however the effects on the company's profitability have not been discussed in detail. This study analyzes the impact from implementing a PCS on the accuracy of calculations in the quotations and the impact on the relative contribution ratios of products. For that reason, a configure-to-order (CTO) manufacturing company has been investigated. A longitudinal study is performed where both the accuracy of the cost calculations and the profitability is analyzed before and after the implementation of a PCS. The comparison reveals that increased profitability and accuracy of the cost estimation in the sales phase can be achieved from implementing a PCS.

1 INTRODUCTION

In today's business environment companies are forced to offer customized solutions without compromising delivery time, quality and cost [1]. In order to respond to those challenges mass customization strategies have received increasing attention over the years, both from practitioners and researchers. Mass customization refers to the ability to make customized products and services that fit every customer through flexibility and integration at cost similar to mass-produced products [2]. Utilizing product configuration systems (PCSs) is one of the key success factors in order to achieve the benefits from the mass customization approach [2][3].

PCSs are used to support design activities throughout the customization process, where a set of components along with their connections are pre-defined and where constrains are used to prevent infeasible configurations [4]. This is one of the reasons why configurations systems are considereded to be among the most successful applications of artificial intelligence [5].

Once implemented, the PCS usually supports the sales and engineering processes in various dimensions, which can lead to numerous benefits such as; shorter lead-times, more on-time deliveries, improved quality of the product specifications, less rework and increased customer satisfaction. Besides, its supportive function PCS enables improved decision making in the early phases of engineering and sales processes [6]. Furthermore, the system can be used as a tool that allows the salesperson to offer custom-tailored products within the boundaries of standard product architectures, thereby giving companies the opportunity to be more in control of their product assortment [7]. As the various benefits are described from implementing a PCS, it can be concluded that those benefits will have direct impact on the company's profitability in terms of increased contribution ratios and more accurate cost estimations in the sales phase. However the link between implementing a PCS and its effects on the company's profitability has not received much attention from researchers, even though it is one of the most critical factors during the planning phase of such a system. Ergo this article focuses on assessing the impact of the implementation of a PCS on companies' profitability by analysing the accuracy of the cost calculations in the sales phase and the profitability of the products in terms of their contribution ratios. Based on this, the following propositions are developed:

Proposition 1 *The accuracy of the cost calculations in the quotations is increased by the implementation of a PCS.*

Proposition 2 *The contribution ratio of products is increased when they are included in a PCS.*

Aiming to investigate these effects, a longitudinal case study was performed. In 2009, an analysis of the product's profitability and accuracy of the cost calculations in the quotations generated in the sales phase was conducted. The results from that analysis indicated that the performance of the sales processes could be improved by the implementation of a PCS. That recommendation was adopted by the company; hence a PCS was developed and implemented in 2011. Three years later, the same analysis was performed in order to determine the impacts on the company's profitability that could be related to the implementation of the PCS. The comparison of the results before and after the implementation of the configurator is assessed and discussed in relevance to the propositions.

This paper is structured in 5 sections. In section 2 the relevant literature will be analyzed in terms of PCSs and the benefits that can be achieved from implementing such a system. In section 3 a case study will be presented where the influence on company's profitability and the accuracy of the cost calculations from implementing a PCS will be analyzed. Then, in section 4 the conclusions from the case study are discussed. Finally, in section 5 discussion about the findings of this research work and future research are presented.

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2 LITERATURE REVIEW

In this section the theoretical background of the present research is reported. In order to find the relevant publications a literature review has been performed in the research area of PCSs.

Forza and Salvador have performed extensive research in this field. The authors present a case-study of an CTO manufacturing company, that identifies the benefits of the implementation of a product configuration tool [8]. The benefits discussed are reduction of delivery time, improved customers' relationships and elimination of errors in Bill-Of-Material (BOM). They quantified the impact that the use of a configuration tool has on lead time, as reduction of manned activities in the tendering process (tendering lead-time from 5–6 days to one day). In addition to that, the errors in the products' BOM, misunderstandings between salespersons and customers are eliminated, while at the same time the level of correctness of product information has been increased, reaching almost 100%. In a related study [7], the authors present a case-study of a manufacturer, who's production strategy is based on customers' orders. After the implementation of a product configurator, one of the benefits identified is reduction to almost zero of the errors in the configurations released by the sales office, in addition to savings in man-hours. There have also been noted significant benefits in production, including manufacturing and assembly processes, due to the fact that by using the configuration tool correct information are received in the production. Furthermore, there has been an increase in technical productivity, both regarding product documentation release and design activities.

To this end, the benefits of using a PCS in the sales process are further investigated [9]. One of the main advantages discussed is that the configuration tool describes the possible configurations of the product in a way that they are simple and understandable by the customer. In that way, it can be ensured that there are no contradicting requirements, no missing specifications and that product configurations produced are valid. Moreover, since the configurator deals with real time information, it helps reducing dialogue time between salespersons and customers. Finally, it is highlighted that any kind of miscommunication between the salespersons and the customers is eliminated and possible errors are reduced. The reason for that is a possible source of errors in the quotations due to the sales personnel lack of technical knowledge.

The use of a product configurator and its effect on product quality is discussed by Trentin et al. [10]. The authors performed a survey in order to verify the relationship between the use of a configurator and the quality of products. The results show a positive effect on product quality by using a product configurator.

Haug et al. [11] discuss possible development strategies for product configurator and evaluate the concluding benefits. Advantages identified are, firstly, the convenience of evaluating information included in the configurator software before implementation and ease of altering implemented product information. Facilitating the communication between product experts and configurator software experts is essential in order to build a configuration tool. This results in minimizing use of resources on documentation work and handovers of information, and rapid implementation of gathered information. The benefits realized are both fewer chances of misunderstandings and errors, and faster processes. Haug et al. [12] performed another study in 14 ETO companies, where the impact of implementing a PCS on lead times is quantified. The results indicate significant improvement for the companies, as it has been measured 75% to 99.9% reduction of quotation lead time.

Another case study performed by Hvam [13] discusses and quantifies the impact from the implementation of a PCS in the electronics' industry. The main benefits from the use of configuration tools are considerably lower costs for specification processes and production. The reason for that is that when specifications are generated in the PCSs, the actual working time for preparing offers and production instructions tends to be near zero. The benefits in that case-study are quantified and show that the fixed production costs have been reduced by 50%. Additionally, the variable production costs have been reduced by 30%. On top of that quality has been improved, and is realized as a reduction from 30% to less than 2% in the number of assembly errors, as well as delivery time has been reduced from 11 – 41 days to one day. After-sales services and installation are also positively affected by the configurator. For instance, the time for replacing a battery has been reduced from 5–6 hours to 20–30 minutes.

Hvam et al. [14] performed another case measuring the impact of implementing a PCS in the ordering process of a CTO manufacturer. It is noted that only a 0.45% of the specification process time is value adding. As a result the non-value adding time spent on making the specifications can be reduced by the use of a configurator. By automating the process fewer errors occur, the productivity of employees is improved and the quality of information and documents is increased. That is due to both reducing the standard deviation of the duration of the processes and avoiding errors in quotations.

Similarly to the previous, another case-study is performed by Hvam et al. [15] in an ETO provider of cement plants. The benefits of the implementation of an IT-supported product configuration in the quotation process of complex products are aligned to those discussed above. In detail, a reduction in lead time from 15-25 days to one-two days for the generation of quotations is noted. An increase in the quality of quotes as it is made possible to optimize the cement plants satisfying better the customer's needs, and making less errors in the specifications made in the PCS. Resources consumption for making quotations is reduced in the engineering department from five man-weeks to one to two man-days.

Aldanondo et al. [16] identify the main benefits as the reduction of cost and cycle time for highly customizable products. That is due to the fact that without the support of PCSs iterative procedures occur in sales and design processes. These activities result in generating longer cycle time and increasing costs.

Slater [17] analyses the benefits of a web-based configurator in CTO environments. By using a PCS the company is able to offer the right product from the very beginning to each customer. The PCS assists the sales personnel to have an overview of the valid configurations and, therefore, avoid mistakes in the communication with the customers. This results in eliminating re-works on the customers' order. The same knowledge embedded in the configurator is used to provide unique manufacturing instructions and to make the rules for the correct configuration accessible to the engineers.

Gronalt et al. [18] outline the benefits of the implementation of a PCS, such as personalized customer support, representation of knowledge and distributed reusability of consolidated product configurations. To this end, Hong et al. [19] discusses the use of a configurator so as to reduce the information and attributes used to configure a product variant in One-of-a-kind production (OKP).

Fleischanderl et al. [20] provide empirical evidence showing that a configurator supporting the product development and production process can reduce the cost of the product's life cycle up to 60%.

The implementation of a PCS in the sales and marketing process has direct effects, such as number of errors, pricing, accuracy, time and cost to reworks, time to validate, reduce order cycle time, improve salespersons' morale, improve customers' satisfaction [21].

Empirical evidence from a built-to-order manufacturer claim benefits such as increase on customer satisfaction, lower costs and higher productivity. In addition to these, an increase in the technical accuracy of orders entering manufacturing processes is noted, which also leads to cost and errors' reduction [22].

Tenhiala and Ketokivi [23] performed a survey in make-to-order (MTO) manufacturing companies and found support to the hypothesis that the use of product configurator software in MTO production processes is positively associated with product conformance. Additional findings indicate that in general the use of configuration management practices in MTO production processes is positively associated with product conformance and delivery performance, among custom assemblers and producers.

Another problem that product configurators should focus on, according to Blecker et al. [5], is the customer perspective. They claim that designers of configurators mainly concentrate on the back-end technical aspects. By process simplification and personalization the wrong interpretation of the customer requirements by the supplier can be avoided. PCSs can therefore be beneficial both for the sales and engineering processes.

Tiihonen et al. [24] conduct a survey in Finish manufacturers with modular-based products. Their findings indicate that in extreme cases 80% of the sales specifications are either incomplete or inconsistent. At the same time, less than 20% of the total working time in the order processing is used for value-adding work. By implementing PCSs there is a reduction to the number of errors related to quality and to quality costs. Moreover, the sales' specification produced by the configurator can be directly used as an input for production, as it will not contain errors. Finally, the configuration can assist the representation of products and product families that are often differentiated in different market areas, and also the transfer of up-to-date product configuration knowledge to the sales units and to enforce its proper use.

Summarizing the findings from the literature review, it can be seen that the implementation of a PCS provides various benefits to the manufacturers, in terms of resources' reduction, reduction of lead time, better communication with customers and product quality. However, there is a lack of empirical evidence on quantifying the impact of the use of a product configuration tool on improved profitability and more accurate cost estimation. This work contributes to that fact, by providing a longitudinal case study, comparing the economic performance of the products and the accuracy of quotations before and 4 years after the implementation of a PCS in a CTO manufacturer.

3 CASE STUDY

In order to examine the propositions a case study is performed. The purpose of this case study is to illustrate the difference between cost estimation accuracy and product profitability, when using a PCS and without one. Therefore, a longitudinal case study is performed, by making similar analysis in 2009, when the company was not using a PCS, and in 2014, 4 years after the implementation of the configurator. The reason for selecting that specific period is to ensure that the PCS has been fully integrated into the business processes of the company, therefore increasing the validity of the comparison. The data for this research was gathered from company's internal databases and was verified with experts from the company.

3.1 Background

The company analysed in this case study is a Nordic company in the building industry that operates worldwide. In the year 2014 the company had around 100 employees and yearly turnover of approximately 15 million Euro. On average the company has around 50 projects per year where the average turnover per project is approximately 300.000 Euro. The company manufactures pre-made structural elements for buildings. The product portfolio consists mainly of six products; A, B, C, D, E and F. The first four products have standard product architecture that can be adjusted to the customers' needs. Products of type E denote to all the non-standardized solutions and products of type F relate to additional features or to the parts that can be added to the standard solutions.

In 2009 the process of making budgetary quotation and the accuracy of the cost estimation were analysed, which revealed the company's performance of accurate cost estimations could be improved. The analysis also revealed that the company's procedure of using Excel sheets to make the calculations of estimating the prices resulted in many errors that could be traced to human mistakes. Based on this analysis the company decided to invest 150.000 Euro to develop a PCS to improve the processes of generating budgetary quotations. The PCS used at the company is a commercial PCS, which builds on constrains propagation. In addition to that, the company also made process improvements and changes in the product assortment that aimed to increase standardisation. The implementation of the PCS also ensured that the salespersons are going to provide the customers with valid configurations from the standard product architecture.

The development of the PCS took place in the period 2009 – 2010, and in beginning of 2011 the company had developed a PCS able to handle most of the budgetary quotations. Only products of type E, which are categorized as non-standard solutions, have not been included in the system. However, due to insufficient change management, not all employees were willing to change their work procedures and therefore they still used Excel sheets to make the cost calculations for making the budgetary offers.

In this case study the impact from implementing the PCS on the company's ability to make accurate price estimations for the budgetary offers and the company's profitability will be assessed. The analyses were done both before implementing the system and for the period of its utilization over, the past 4 years (2011-2014). Thereafter the accuracy of the calculations made by using the Excel sheets and the PCS will be compared.

3.2 Analysis of the Company's Performance Before and After Implementation of Product Configuration System

In order to compare the performance before implementing the PCS (2009) and after the implementation (2011-2014), contribution margins (CM) and contribution ratio (CR) were calculated for each project that had been carried out at the company within the timeframe of this research. Those calculations where both based on the estimations of the budgetary quotations and both the real cost and sales prices calculated after each project had been closed. CM and CR are calculated as follows [25]:

$$CM = Sales\ Price - Cost\ Price \quad (1)$$
$$CR = CM \,/\, Sales\ Price \quad (2)$$

Finally, the deviation in the CR is then calculated as actual CR minus the estimated CR.

$$DEV = CR_{actual} - CR_{estimated} \quad (3)$$

If the real cost of the project is higher than the estimated cost, it will result in negative deviation of the CR. Respectively, if the real cost of the project is less than the estimated it will result in positive deviation in the CR. The data for the analysis was extracted from the company's internal database and verified with specialist at the company. The cost prices of the projects were calculated as the sum of the costs for expenses on construction site, subcontractors, materials and salaries. The projects included in the comparison are from 2009, when only the Excel sheets were used to calculate the cost, until 2014. For the period 2011-2014 the cost calculations are either done in the PCS or by using Excel sheets. In Table 1 the main results from the analysis are listed.

Table 1. Overall analysis of the PCS contribution in terms of CR before implementation (2009) and after implementation (2011-2014)

	Performance indicators			
Year	◊	□	○	◊◊
2009	-1.5%	5.4%	14.6%	25.0%
2011	-3.6%	7.7%	28.5%	25.5%
2012	-0.7%	4.9%	8.9%	27.6%
2013	-2.4%	4.9%	9.5%	28.8%
2014	-1.1%	3.9%	2.2%	28.6%

◊ Average difference in CR □ Average absolute deviation in CR ○ Percentages of projects with greater deviation than 10% ◊◊ Average CR per project

The analysis shows that the average CR has steadily increased from 25.0% in 2009 to 28.6% in 2014. However, the overall company's goal is to have projects with CR of 30%.

The deviations in the CR also show positive improvements as the average deviations have been reduced from -1.5% in 2009 to -1.1% in 2014. Regarding the absolute value of the CR, when analyzed, the deviations showed reduction from 5.4% to 3.9%. It should also be noted that the percentages of projects with greater deviation than 10% have been significantly reduced from 14.6% in 2009 to 2.2% in 2014, as the calculations of the absolute values in the CR indicate. However in 2011, which was the first year when the PCS was utilized, the deviations in the CR increased considerably. This increased in deviations can be traced to the fact that the system had not been fully tested before implementation and the users of the system were lacking training. But as the users became more experienced in using the system and errors had been fixed, the PCS started providing valuable results.

This analysis indicates that the calculations are now more precise than before the implementation of the PCS and the company is moving closer to the targeted CR, which is 30%.

3.2.1 *Analysis of Cost Structure and Deviations*

In this section the company's cost structure and the deviations in the estimated and actual values with regards to the main cost elements is analysed. The purpose of that analysis is to identify whether cost estimations have been improved after the implementation of the PCS by analysing the main cost elements. The cost elements that are included in the analysis represent the direct cost of making the product, which covers the expenses related to materials, salaries, subcontractors and for the construction site, e.g. renting machines.

In 2009 a cost analysis was performed in order to assess the economic benefit by implementing a PCS. This benefit is highly associated to the reduction of deviations in the cost estimation, as the application of a PCS would thereby improve the budgetary quotations. In Figure 1 the results from the analysis are shown for the deviation in the CM for the cost calculations of the main cost elements.

Figure 1. Deviations in cost estimations for the projects 2009 distributed between the main cost elements

The figure above shows great deviations and irregularities in the pattern, which indicate that only a few projects were realized at the same cost as calculated. This means that the salespersons have estimated significantly lower costs for the projects than the actual ones, as the deviations are mainly negative. That means that the sales persons underestimated the cost of the project. That refers to all different cost categories, as they all deviate towards the same direction (positive or negative). Based on this it can be concluded that the accuracy of the calculations for the budgetary proposals were inadequate in 2009.

In order to see whether the situation has been improved at the company since implementing the PCS, a similar analysis was repeated in 2014, three years after implementing the PCS. The results from the analysis are shown in Figure 2.

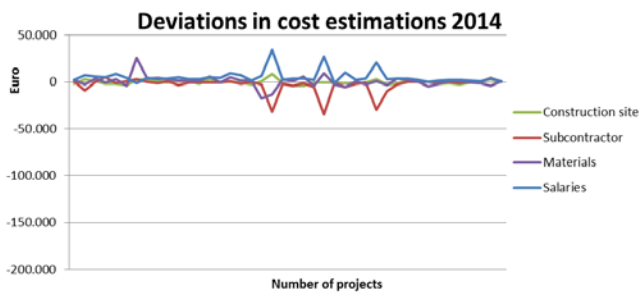

Figure 2. Deviations in cost estimations for the projects in 2014 distributed between the main cost elements

As illustrated in the above figure, when comparing the deviations in CMs of the projects from 2014, it can be clearly noted that there are far less fluctuations in the cost calculations than in 2009. Beside a few projects, the majority of them have rather low deviations from the calculated budget. By comparing the results from Figures 1 and 2, it can be realised that the accuracy of cost estimations has been improved since implementing the PCS. This is also supported by the fact that the deviations from 2009 for all the cost elements are not towards the same direction, meaning that in 2009 the deviations were negative in their overwhelming majority.

The costs in 2014 are closer to the baseline; nevertheless, three large negative spikes for the subcontractor category can clearly be seen, on the same projects with the positive spikes for the salaries. From an interview with a specialist at the company the reason for the large deviations in these three projects was due to the fact that the construction work was outsourced to subcontractors. This explains why the subcontractor category reveals large deviation and at the same time there is a positive deviation in the salary category, as the work was outsourced and therefore salaries to own employees could be reduced for the projects.

In the project where there is a large positive deviation in the material category. The explanation given was that from the time the proposal was given out and until it was finished it took several years and in the meantime a new steel structure was developed and implemented, which was much cheaper than the old structure. The large positive deviations in the cost estimations that were noticed in the 2014 analysis have therefore been reasonably explained. In the next section a more general explanation for the deviation is provided.

3.2.2 Reasons for the deviations

In order to gain a better understanding of the deviations in the cost estimations, a deeper analysis is performed, with the aim of clarifying why these deviations are still occurring at the company. The most significant deviations in the projects 2014 have been explained above, however in this section additional factors that influence the deviations will be further analysed.

The company aims to provide the customers with high quality service therefore if a customer wants to make changes to the specifications later in the process, the company will strive to adjust the solution to satisfy the customer's wishes. When such changes occur, the additional cost is added manually to the total price. This makes the actual cost of the project deviate from the initially calculated cost, but does not affect the profitability of the project.

Furthermore, the cost at the construction site is difficult to estimate since there are frequently unforeseen factors which have to be dealt with, such as difficulties to get the machines at the building side. That can result in increasing the time that the machines have to be rented and creating additional expenses due to salaries of subcontractors, which were not taken into account in the original calculation of the estimated cost. However, this threat could be reduced if technicians would examine the construction site in order to make more realistic estimations of the cost.

However, it worth mentioning that the highest peaks in the deviations of the cost calculations in 2014 are not caused by errors in the quotations, or additional costs due to unforeseen factors at the construction site but mainly because of the outsourcing work to subcontractors. Under certain circumstances, time can be limited and the company's employees might get closer to a deadline for a project and the construction team cannot finish on time. Then it might be necessary to outsource the work to subcontractors to finish on time and not delay the project, as that will also cause higher additional cost.

It can be concluded from the above analysis that the main reasons for the deviations in the cost calculations were not due to inconsistences of the PCS. Late changes from the customers, unforeseen circumstances and outsourcing are some of the main factors reported by the project managers of the company, which when occur, cause deviations in the cost calculations.

3.3 Comparison of Budgetary Proposals Made in Excel and PCS

In 2011 the PCS was first launched in the company. However, it has not been accepted by all sales representatives therefore some of them were still using Excel sheets for the calculations. The main reason for that is the lack of change management initiatives, which resulted in some employees resisting to use the PCS and therefore sticking to their old work habits. In this chapter the yearly turnover, CR of the projects and the deviations of the CR will be analysed in terms of whether they were generated by the Excel sheets or the by the PCS.

The turnover generated by projects sold through the PCS has been steadily increasing since 2011. In the year 2013 the point was reached, where slightly more proposals were generated by the use of the PCS. Figure 3 shows the yearly turnover for the proposals made in Excel and by use of the PCS.

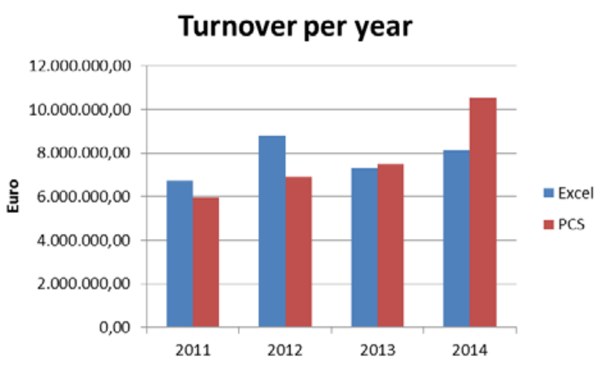

Figure 3. Comparison of turnover generated for proposals made in Excel and by use of the PCS

As can be seen from the above figure, in 2011 and 2012, the projects handled by the salespersons through the Excel sheets contributed more to the turnover of the company; even though the PCS has already been implemented in that period. This can be explained, firstly, by the reluctance that some of the salespersons showed towards including the new PCS in their working processes, as they still used Excel for the cost calculation and quotation generation. Additional, the period 2011-2012 was the initial introduction of the PCS at the company. However, the PCS did not include all products at that point of time; therefore its utilization was by definition limited. As a consequence, during the trial period the turnover contributed by the projects handled in Excel is higher than the one from the PCS, but this fact was significantly changed in the following 2 years. So, in the period 2013-2014, when the company managed to take greater advantage of the PCS, and its utilization was strongly established, the turnover of the projects worked out by using the PCS outnumbered the ones worked out in Excel.

3.3.1 Sales Representatives and CR

The company's goal is that all projects should have a CR of 30%. An analysis of the overall performance of the company, (section 3.2) showed how the CR has been increasing since 2009. However, in order to confirm that this can be traced to the implementation of the PCS, a comparison of the CR for the budgetary proposal made by using the PCS and Excel is performed. In Figure 4, the actual CR is illustrated for the proposals made by use of the PCS and Excel.

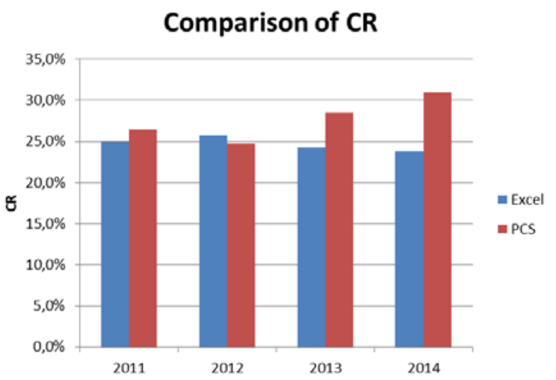

Figure 4. Comparison of CR for salespersons using Excel and PCS

From this it can be concluded that salespersons using the PCS contribute a higher CR, with an exception in the year 2012 where it was slightly lower. Furthermore, it can be seen that the gap between the CR is increasing between the salespersons using Excel and the PCS. In 2014 the average CR was 28.6%, where sale persons using the PCS had average CR 30.1% while sale persons using Excel had 23.8%. In other words, the salespersons using the PCS have managed to achieve the goal of 30%.

However as previously mentioned the products of type E, which are the non-standard products, are not included in the PCS therefore in order to make the price estimation Excel sheets are always used. Even though those products are not included in the calculations for the proposals made in Excel, when they were taken into account they only affected the CR for the proposals made in Excel by 0.2%. Therefore it can be concluded that the reason for lower CR cannot be traced to the special orders.

Another important factor is to compare the deviations in the CR between the proposals made in Excel and PCS. The results are illustrated in Figure 5.

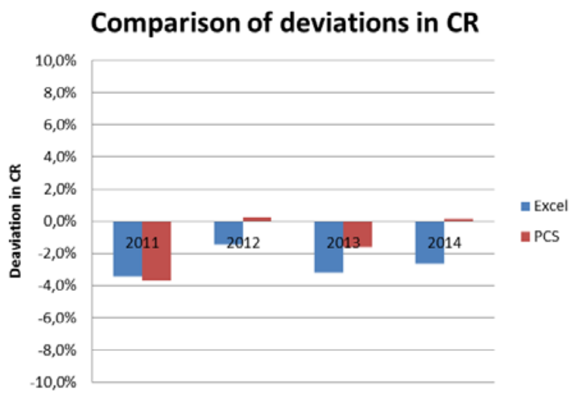

Figure 5. Comparison of deviations in CR for sale persons using Excel and PCS

As it can be seen from the above figure, the salespersons using the PCS have less deviation in their CR than the ones using Excel, with the exception of the year 2011 which was the first year the system was used in the company. Moreover, in 2012 and 2014 the deviations of the quotations made by the PCS are positive and close to 0.

The analysis of the performance of the salespersons using Excel and PCS therefore indicates that the PCS affects positively the accuracy of the cost estimation as well as the CR. Summarizing the results from this section, it can be seen that both the CR and the accuracy of estimations are improved by the utilization of the PCS. To this end, it can be concluded that the both propositions are supported by the results of the case study.

3.4 Future Initiatives

In order to improve the company's performance several factors have been identified that could reduce even further the deviations in the CR and increase the profitability of the company. The company intends to implement a check list in the end of each configuration in order to ensure that all the required information is both gathered in the sales phase and up-to-date. By implementing the check list, it is expected that errors made in the sales process will be reduced even further. Furthermore, the company is planning to enhance a higher degree of standardization in their product range, as well as move towards modular based product architecture. Finally, the company has decided to invest 140.000 Euro in further development of the PCS, in order to include more products and have greater benefits from its utilization.

4 CONCLUSIONS

The scope of this case study is to quantify the impact of implementing a PCS on product profitability and accuracy of cost estimation. The research results in significant improvements in both the CR of products sold through the PCS and the accuracy of quotations. These results confirm the propositions made in this paper. In detail, an improved performance of the margins of the products is recorded, as well as a reduction in the deviation of quotations. The comparison in the quotations' deviation is made between the same products, sold in 2009, before the company implemented the configurator, and in 2014, when the sales process was supported by the PCS. Moreover, there is a comparison between the CR of products being sold with and without the use of the configurator for the period 2011 to 2014, when the PCS has been implemented and used to its full potential. Both comparisons lead to the same conclusion, that the contribution of the PCS is noteworthy, as the performance of the products included in the PCS is improved. Additionally, the deviations between the initial quotation provided to the customer by the PCS and the actual cost of each project are eliminated. Since the data used in the PCS is updated and all possible solutions are validated before making an offer, the quotation includes fewer errors and more accurate price estimation, when it is compared to the quotations of the products not included in the PCS.

5 DISCUSSION AND FUTURE RESEARCH

This work focuses on the benefits of implementing a PCS in a configure-to-order manufacturing company. The benefits widely discussed in the existing literature are directed towards customer satisfaction, cost reduction due to a better use of resources and elimination of errors, and improved product quality. The empirical evidence provided in this research is based on a single case study. However, the company is considered to be a typical example and highly representative in the configure-to-order industry.

This research is the first step in exploring the impact of a configurator on product's profitability. Hence, similar cases also need to be examined, in order to compare the profitability between projects going through the PCS and outside of it. By examining more cases, a deeper understanding can be gained and a more detailed explanation of the correlation between configuration tools and product profitability can be provided.

In this paper empirical evidence is provided by only one case study. Yet, the impact registered in this company indicates that there could be significant impacts from implementing a PCS, which have not been discussed in the literature previously. Therefore, this requires further research and additional case-studies in order to justify the underlying correlation between PCS and profitability increase.

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ARTICLE F

Impact of the utilization of a product configuration system on product's life cycle complexity

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Abstract
The purpose of this paper is to identify areas throughout a product's lifecycle processes where complexity can be reduced by implementing a product configuration system (PCS). As discussed in the literature, several benefits are realized by using a PCS in terms of product and process standardization. This also leads to control and reduce of complexity both in products and processes. To this end, this research attempts to quantify and assess these benefits and is supported by empirical evidence. A case study of an engineering company is used and the results indicate significant improvements for the company in several life cycle processes.

Keywords: Complexity, Product Configuration System (PCS), Product life cycle

Purpose
This paper aims to pursue the research opportunity of exploring the overall impact on complexity reduction throughout the products' life cycle by implementing a product configuration system (PCS) in the early sales phase (Figure 1). The literature describes various benefits that can be gained from implementing PCSs, however the connection between those benefits and the effects on complexity reduction in the different phases of the products' life cycles has not been explored to full extent. This research focuses on engineer-to-order (ETO) companies; we consider companies that sell complex and highly engineered products, such as cement or chemical factories, oilrigs etc.

Complexity in a manufacturing environment can be identified in products, processes and organization (Wilson and Perumal, 2009), and it lies upon each of those aspects but also in their interrelationships (Blecker et al., 2006)(Samy and ElMaraghy, 2012). There are several factors identified in the literature related to complexity of products' life cycle (ElMaraghy et al., 2012).

Additionally, the various benefits from the implementation of a PCS are discussed in the literature. PCSs have been implemented widely to support the specification process for the customized products and guide the sales process (Zhang, 2014). The benefits from applying PCSs can be described in terms of shorter-lead time and improved quality of the product's specifications, reduced resource consumption and increased customer satisfaction (Tiihonen et al., 1996). The ability to make the right decisions in early stages of the sales and engineering processes is increased as sales persons and the customers are guided through the process by the PCS (Gronalt et al., 2007)(Slater, 1990). For that reason, less rework and less iterations are required, as the quality and the accuracy of quotations are increased (Hvam et al., 2004). Furthermore, PCSs can be used as tools that support sales persons to offer customized products within the boundaries of standard product architectures and thereby enable companies to be more in control of their product assortment (Forza and Salvador, 2002)(Fleischanderl et al., 1998).

As a result this research combines the fields of PCS and complexity, by identifying factors that indicate how product's life cycle complexity can be reduced by the utilization of a PCS.

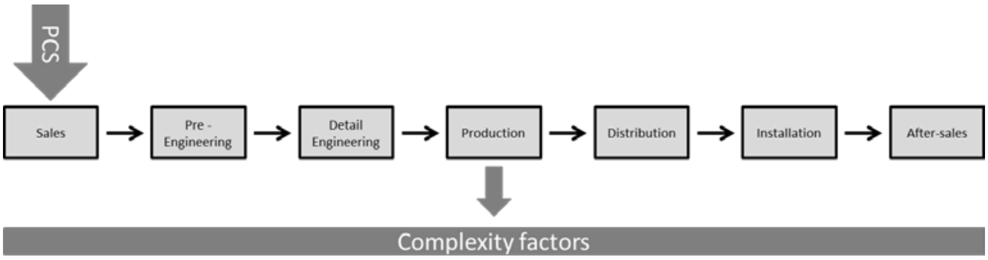

Figure 1 - Impact from implementing PCSs in the sales process on the different phases of the product's life cycle

Methodology

This paper examines the existing literature on the utilization of PCSs in ETO companies and quantifies the impact that a PCS has on the different phases of a product's life cycle. The aim of this study is to identify complexity factors in the different phases of a product's life cycle that are affected by the utilization of a PCS. The research is supplemented with empirical evidence based on a case study of a representative ETO company within the oil and gas industry. The unit of analysis is the different projects for a four-year period of time, which include both complete projects of oilrigs and sales of single equipment. The study follows a research protocol to ensure internal and external validity of the approach (Yin, 1994).

Findings

In the four-year time period, the company sold 12 projects and 193 single products. Based on the data acquired, the revenue for the projects is 743,5 m€ and for the single products 46,5 m€. Respectively, the costs are 758,7 m€ for the projects and 30,9 m€ for the single products. It can be seen from the numbers above that even though the projects create higher revenue compared to the sales of single equipment, the related costs are even higher, resulting in loss for the company. Furthermore, for the projects sold a deviation is identified between the estimated cost and revenue at the beginning of the project, when the budget is calculated, and the actual ones, when the project is finished.

An area of interest identified during the analysis of the financial performance of the projects is the reduction of cost through repetition. When a project is re-produced based on an existing one, several cost categories are identified to have noteworthy reductions. This trend of cost reduction through reusability is identified in several costs which are related to different life cycle processes, such as production, engineering hours, the revisions of drawings and changes on the drawings, outsourced production equipment and commissioning.

Based on the analysis of the financial performance of the company two main areas of potential improvement can be identified as discussed in the literature (Jiao et al., 2007) (Blecker and Abdelkafi, 2006); standardization and reusability. In order to achieve these improvements, firstly, the company should increase the standardization of the product portfolio. By changing or adjusting the products' architecture, the company can seize the benefits of complexity reduction in the product assortment. Then, the standardization of the processes and the increase in material reusability can be achieved by implementing a PCS. Through the utilization of a PCS both product and process complexity can be reduced and this would have a direct effect of cost savings.

Conclusion

The scope of this study is to identify how the implementation of PCSs affects the complexity, in terms of cost reduction, through the different phases of a product's life cycle. By following the suggested method, areas that are improved by the implementation of a PCS are identified and the related cost improvements are quantified. Some examples of cost reductions are those related to production, engineering, documentation and specification processes. Regarding the case study, the potential savings vary from 4% to 15% throughout the entire products' life cycle as a result of the complexity reduction related to the implementation of the PCS.

Contribution

This research aims to provide an in-depth overview of the main complexity factors that can be addressed by the implementation of the PCS through the products' life cycle. By bridging the gap between the theories of PCS and complexity management, this study aims to assist in optimizing the potential benefits in terms of complexity reduction by the implementation of a PCS in the early phase of the sales process in manufacturing companies.

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ARTICLE G

Identification of complexity cost factors in manufacturing companies

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Identification of complexity cost factors in manufacturing companies

Complexity tends to be arguably the biggest challenge of manufacturing companies. This research focuses on the relationship between product and process complexity. The possible factors for describing this correlation are identified and defined as complexity cost factors (CCFs). The study is supplemented with empirical evidence from applying some of the cost factors identified. Firstly, based on the literature study, CCFs are identified and categorized by using the industrial standard APQC for process classification. Then, this categorization is used as a tool for identification of CCFs in seven companies. This study aims at developing a practical tool both for academia and practitioners to be used as a guide when analyzing and quantifying complexity costs in manufacturing companies. The results on the analysis of complexity obtained in the case companies are evaluated and future work is discussed.

Keywords: process complexity; product complexity; complexity cost; complexity management

1. Introduction

Complexity is a field of increasing interest, both for researchers and practitioners. Recent surveys conducted by IBM (2010) show that the main concern of 1,500 chief executive officers (CEOs) is the increasing complexity, which is considered to be the biggest threat for an organization. A survey performed by ATKearny (2009) in over 100 companies from more than 10 industrial sectors revealed that 84% of the companies consider complexity as a key cost factor, and that lack of transparency over complexity costs leads to inefficient management of complexity. The impact of product and portfolio complexity on operations and processes across the entire value chain is recognized by the managers, and is realized in different ways by each of them. For instance, plant managers face complexity caused by products in the form of increasing complexity in production planning and scheduling, supply chain managers in increasing inventories and finance managers in growing level of investment in fixed assets (Brown et al. 2010). Ergo, complexity affects all business processes and it is being expressed in different ways. The causes for increasing complexity costs are specific for each company. In order to identify and quantify the most critical causes of complexity in a specific company, we need to identify the factors describing how product complexity leads to increased complexity and costs in a specific area of a company. For this we introduce the concept of a Complexity Cost Factor (CCF).

We define a CCF as a factor that causes uneven distribution of the costs among the different products. For example, the set up and change over times of the machines in production vary among the different products, as well as the batch size in a way that high volume products would have relative low set up cost per item, while low volume products would have relative high costs per item. By assigning the actual set up time for each and every product, differences are noted to what was considered to be fixed cost, and was so far distributed equally among all the products. In order to calculate and reduce complexity costs, but also to reveal the real contribution of each product to the profit, the need of calculating the complexity cost becomes imperative. A CCF is a factor that describes how product portfolio complexity (e.g. number of finished goods) has an impact on the costs of a specific process step. Examples of CCFs are setup times in production, scrap of materials in setup of machines, sales order handling, inventories of finished goods, and freight of finished goods to warehouses.

By identifying the CCFs we intend to analyze the most relevant processes where the complexity and cost are directly related to the complexity of products. In this way, it will be possible to quantify the exact cost impact on those processes for each product variant (e.g. one specific product would have a cost of set up cost per product at 3 euro per product, while another product would have a setup cost at 30 euro per product due to relative smaller batch sizes. By this we can allocate the specific costs of complexity to each product thus making a more exact quantification of the costs of complexity per product. This makes it possible for the company to evaluate the product range and eventually eliminate low volume products with relative high complexity costs. The approach differs from Activity Based Costing in that we strive to identify the most significant CCFs and only allocate these costs elements to the products. Furthermore we focus in particular on the correlation between complexity in the product assortment and the cost of processes.

1.1 Problem Statement and Delimitation

According to Wiendahl and Scholtissek (1994) complexity in industrial manufacturing environments is related to products and production, and production complexity is divided into structural (structures) and dynamic (procedures). Complexity is three-dimensional, as it rises in products, processes and organizational structure, and there is an interconnection and a strong impact among these three types of complexity (Wilson and Perumal 2009).

Complexity in the products leads to complexity in operations (Blecker et al. 2006). In this article, we mainly focus on costs implications from product complexity on sales, production and delivery (Samy and ElMaraghy 2012a). Additionally, we neither consider other implications like on-time delivery, time of delivery, quality, ability to introduce new products, nor the process step of product development. In order to make an in-depth analysis, only parameters addressing costs are taken into account (Wang et al. 2011). Aiming to quantify the impact from product complexity we need to relate a specific product assortment with a specific number of components and number of finished goods and quantify the impact from reducing or increasing the number of components or number of finished goods on the costs of a specific process step.

The assessment of product profitability and cost behavior (Wan, Evers, and Dresner 2012) has been discussed in terms of managing complexity product- and process- wise (Danese and Romano 2004; H. ElMaraghy et al. 2013). Hence the purpose of this paper is to identify and classify possible CCFs in manufacturing companies. Then, CCFs are grouped and categorized under the APQC industrial standard of process classification (APQC 2015), in order to provide an overview and a practical approach for identification of relevant factors to apply in a specific company. These factors identified are further to be used for analyzing and quantifying costs caused by complexity in manufacturing companies. The results of this research contribute to the development of an approach for managing complexity in manufacturing companies, in addition to product variety control and optimization of production processes.

2. Theoretical Background

In order to define the conceptual framework of this research, a literature review is performed. The main keywords for searching are "complexity cost factors", "product complexity", "process complexity" and "complexity drivers". The reason for introducing the term "driver" is the fact that early in the review process, it has been noted that many articles use this term within the same meaning as others use the term "factor", such as Perona and Miragliotta (2004) and Schaffer and Schleich (2008). However, both words when used in the articles reviewed refer to facts that cause, stimulate and increase complexity.

2.1 APQC process classification standard

The next step of the literature review focuses on identifying a framework for classification of processes. The reason for using such a framework is to obtain an overview of the processes in a manufacturing company, enable comparison among the organizations and categorize the CCFs under the relevant processes. The industrial standard APQC provides such a process classification (APQC 2015). The APQC standard is selected as a classification framework because it describes all the processes in every industrial environment; as a result, it can be applied to any manufacturing company. The APQC process classification framework creates a common ground for organizations that operate in different production and market areas, and it is claimed to be "*the most used process framework in the world*" (APQC 2015).

2.2 CCFs

Several authors have performed literature review studies in the research field of complexity. Bozarth et al. (2009) discuss the main factors responsible for complexity in the whole supply chain, from manufacturing schedule to globalization of the supply chain. Marti (2007) presents the existing concepts in managing product complexity and assesses them with five criteria, such as product strategy, market aspects, product architecture, quantification methods and applicability in practice. Five areas of complexity are identified by Foster and Gupta (1990): product design, procurement, manufacturing process, product range, and distribution.

Forza and Salvador (2002) examine the benefits of implementing a product configuration system in a configure to order (CTO) manufacturer. In order to assess these benefits, the ordering and production processes have to be examined. This resulted in identifying the number of finished goods as the main source of complexity in both the information flow from the sales personnel to production and shop floor activities. The complexity in the production and assembly processes, identified in supply, production scheduling and manual assembly operations, is highly related to both number of components and number of finished goods (Hu et al. 2011). Huatuco, Burgess, and

Shaw (2010) discuss entropy-related complexity both in the production floor, and in the supplier and customer interfaces.

One cause of increasing complexity in manufacturing environments is the product variety (Schaffer and Schleich 2008). The effect of product variety is related to inventory and production costs. In tandem with these results, Wildemann (2001) performs an empirical study in manufacturing industries, regarding how the number of product variants affects the unit costs. Two types of industries are examined, with traditional and segmented and flexible automated plants. The results have shown that with the double number of product variants in the production program, the unit costs would increase about 20-35% for industries with traditional manufacturing systems. At the same time, in segmented and flexible automated plants, the unit costs would increase about 10-15%.

Nevertheless, complexity is one the reasons that not every variant contributes positively to the net revenue of the company. The profitability of each product variant is, in addition, related to the production flow in terms of lot size and stock keeping units (SKU) (Yücel et al. 2009). W. H. ElMaraghy and Urbanic (2003) introduce two factors of increasing complexity, firstly the number and diversity of features to be manufactured, assembled and tested, and secondly, the number, type and effort of the tasks required to produce the features. Samy and ElMaraghy (2012b) define complexity as “a measure of how product variety can complicate the production process”.

Calculation of complexity costs is an area of particular interest for this research, as the focus is to rationalize a product program in order to allocate the true complexity costs on the product variants (Hansen, Mortensen, and Hvam 2012). Several research groups have been identified in this field discussing frameworks for assessing product profitability and cost behaviour (Zhang and Tseng 2007; Wilson and Perumal 2009;

Danese and Romano 2004; Sivadasan et al. 2006; H. ElMaraghy et al. 2013; Mariotti 2008; Wan, Evers, and Dresner 2012; Wang et al. 2011).

Blecker et al. (2004) suggest mass customization as a strategy for eliminating complexity caused by increasing variation in product architecture, inventory and order taking process. Additionally, they discuss the relations between mass customization and complexity. Mass customization principles are investigated from two different perspectives. On the one hand, when applied as a pure customization strategy, they increase the product variety, which results in high planning and scheduling complexity. On the other hand, as customer ordering decoupling point moves towards the front-end, then mass customization reduces product configuration and inventory complexity. (Blecker et al. 2004)

2.3 Categorization of CCFs under the industrial process standard

The following tables (1-5) provide an overview of the results from the literature review. Each table refers to one of the process groups, as they are described in the APQC process classification framework. Each table describes the CCFs related to a process group, as described in the APQC standard. Under each CCF, the authors working with it are listed. When the names are in bold, it means that the article discusses quantification methods. When parentheses follow the name of the authors, they indicate that there is empirical evidence, such as case-study (CS), survey (S) or numerical example (NE). Articles are listed into two groups with reference to discussing the CCFs related to the number of components and/or the number of finished goods, taking into account both their quantity and diversity/variety.

Table 1 – Articles discussing “Plan for and align supply chain resources”

No of components

No of material handling systems	**Kuzgunkaya and ElMaraghy 2006** (CS), **Samy and ElMaraghy 2012a** (CS)**, Garbie and Shikdar 2011a** (NE)**, ElMaraghy et al. 2012** (CS)
State of material handling systems	**Kuzgunkaya and ElMaraghy 2006** (CS), **Samy and ElMaraghy 2012a** (CS)
Type of material handling systems	**Kuzgunkaya and ElMaraghy 2006** (CS)**, Garbie and Shikdar, 2011a** (NE)**,** **Samy and ElMaraghy 2012b** (CS), **Zhang and Tseng 2007** (CS)
Material flow pattern	**ElMaraghy et al. 2014** (CS)**, Samy and ElMaraghy 2012a** (CS)**, Thyssen, Israelsen, and Jørgensen 2006** (CS)**, Garbie and Shikdar 2011a** (NE)**,** Hayes and Clark 1985 **,** Urbanic and ElMaraghy 2006 (CS)**,** Khurana 1999, Isik 2009

In the table above, all the identified CCFs from the literature are listed. These factors refer to the activities of supplying and planning of the resources, as a result they are relevant only for the number of components but not applicable for the number of finished goods. In this context of a manufacturing industrial environment raw material are considered as resources. That is the reason why the CCFs refer to the material handling systems and flow. All four CCFs identified in the literature are supported by empirical evidence, mainly case-studies and numerical examples.

Table 2 - Articles discussing “Procure materials”

	No of components
No of suppliers	**ElMaraghy et al. 2012, Hu et al. 2008, Perona and Miragliotta 2004** (CS)**,** **Jacobs 2013,** Isik 2009, **Bozarth et al. 2009** (S)
Location of suppliers	**Hu et al. 2008**
Cost of sourced components	**Foster and Gupta 1990** (CS)

The second table presents the factors related to procurement. Suppliers, regarding their number and location, are identified as CCFs related to the number of components. As it is mentioned above, the CCFs are relevant only for the number of components but not applicable for the number of finished goods. For example, by having fewer suppliers the company could achieve lower prices for the materials bought, as they are getting higher volumes. In that sense, the number of suppliers causes uneven costs to the products. Quantification examples are also provided in the literature for the CCFs identified above, in addition to empirical evidence.

Table 3 - Articles discussing “Produce/Manufacture/Deliver product”

	No of components
Capacity utilization	**ElMaraghy et al. 2012, Garbie and Shikdar 2011a** (NE), Blecker and Abdelkafi 2006, Isik 2009
Assembly	**ElMaraghy et al. 2012, Hu et al. 2008, ElMaraghy et al. 2014** (CS)**, Samy and ElMaraghy 2012a** (CS)**, Thyssen, Israelsen, and Jørgensen 2006** (CS)**,** Blecker and Abdelkafi 2006**, Samy and ElMaraghy 2012b** (CS)**, Khurana 1999,** Isik 2009
Tools	**Hu et al. 2008, Samy and ElMaraghy 2012a** (CS)**, Deshmukh, Talavage, and Barash 1998** (NE), Urbanic and ElMaraghy 2006, **Zhang and Tseng 2007** (CS)
Operator	**Hu et al. 2008,** Urbanic and ElMaraghy 2006 (CS)**,** Gershwin 1994, **Zhang and Tseng 2007** (CS)
No of machines	**Kuzgunkaya and ElMaraghy 2006** (CS)**, ElMaraghyet al. 2014** (CS)**, Samy and ElMaraghy 2012a** (CS)**, Garbie and Shikdar 2011a** (NE)**, Deshmukh, Talavage, and Barash 1998** (NE), **Perona and Miragliotta 2004** (CS)**, Samy and ElMaraghy 2012b** (CS)**,** Urbanic and ElMaraghy 2006 (CS), Isik, 2009, **Zhang and Tseng 2007** (CS)
Type of machines	**Kuzgunkaya and ElMaraghy 2006** (CS)**, Garbie and Shikdar 2011a** (NE)**, Samy**

	and ElMaraghy 2012b (CS)**,** Urbanic and ElMaraghy 2006 (CS)
State of machines	**Kuzgunkaya and ElMaraghy 2006** (CS)**, Samy and ElMaraghy 2012b** (CS)
No of buffers	**Kuzgunkaya and ElMaraghy 2006** (CS)**, Samy and ElMaraghy 2012b** (CS)**, Samy and ElMaraghy 2012a** (CS)**, Khurana 1999**
Type of buffers	**Kuzgunkaya and ElMaraghy 2006** (CS)**, Samy and ElMaraghy 2012b** (CS)
State of buffers	**Kuzgunkaya and ElMaraghy 2006** (CS)**, Samy and ElMaraghy 2012b** (CS)
Failure	**Kuzgunkaya and ElMaraghy 2006** (CS)**, Samy and ElMaraghy 2012a** (CS)**,** Hayes and Clark 1985, **Urbanic and ElMaraghy 2006** (CS)**,** Gershwin 1994, **Zhang and Tseng 2007** (CS)
Set up	**Thyssen, Israelsen, and Jørgensen 2006** (CS)**, Garbie and Shikdar 2011a** (NE), **Deshmukh, Talavage, and Barash 1998** (NE), **Benjaafar et al. 2004,** Hayes and Clark 1985**,** Urbanic and ElMaraghy 2006 (CS)**,** Gershwin 1994, **Zhang and Tseng 2007** (CS)
Change-over	**Thyssen, Israelsen, and Jørgensen 2006** (CS)**, Garbie and Shikdar 2011a** (NE), **Deshmukh, Talavage, and Barash 1998** (NE), **Benjaafar et al. 2004,** Hayes and Clark 1985**,** Urbanic and ElMaraghy 2006 (CS)**,** Gershwin 1994
Waiting times	**Thyssen, Israelsen, and Jørgensen 2006** (CS)**, Garbie and Shikdar 2011a** (NE), **Deshmukh, Talavage, and Barash 1998** (NE), Hayes and Clark 1985**,** Urbanic and ElMaraghy 2006 (CS)**,** Gershwin 1994
Batch size	**Thyssen, Israelsen, and Jørgensen 2006** (CS)**, Garbie and Shikdar 2011a** (NE), **Deshmukh, Talavage, and Barash 1998** (NE), **Benjaafar et al. 2004, Zhang and Tseng 2007** (CS)
Capital costs (rent/heating)	**Thyssen, Israelsen, and Jørgensen 2006** (CS)**, Perona and Miragliotta 2004** (CS)
Production lines	**ElMaraghy et al. 2012, Kuzgunkaya and ElMaraghy 2006** (CS)**, Hu et al. 2008, Garbie and Shikdar 2011a** (NE), Blecker and Abdelkafi 2006**, Deshmukh,**

	Talavage, and Barash 1998 (NE), **Jacobs 2013**
Job shop	**Deshmukh, Talavage, and Barash 1998** (NE), **Khurana 1999, Zhang and Tseng 2007** (CS)
	No of finished goods
Capacity utilization	**ElMaraghy et al. 2012, Hu et al. 2008, Garbie and Shikdar 2011a** (NE), Blecker and Abdelkafi 2006, Isik, 2009
Assembly	**ElMaraghy et al. 2012, Hu et al. 2008, Samy and ElMaraghy 2012b** (CS), Blecker and Abdelkafi 2006**, Samy and ElMaraghy 2012a** (CS)**, Schaffer and Schleich 2008** (CS), Isik 2009
Tools	**Hu et al. 2008, Samy and ElMaraghy 2012a** (CS)**, Garbie and Shikdar 2011a** (NE), **Deshmukh, Talavage, and Barash 1998** (NE), **Zhang and Tseng 2007** (CS)
Operator	**Hu et al. 2008, Zhang and Tseng 2007** (CS)
No of machines	**Kuzgunkaya and ElMaraghy 2006** (CS)**, ElMaraghy et al. 2014** (CS)**, Samy and ElMaraghy 2012b** (CS), Sivadasan et al. 2002 (S)**, Garbie and Shikdar 2011a** (NE)**, Deshmukh, Talavage, and Barash 1998** (NE)**, Samy and ElMaraghy 2012a** (CS), Isik 2009, **Zhang and Tseng 2007** (CS)
Type of machines	**Kuzgunkaya and ElMaraghy 2006** (CS)**, Garbie and Shikdar 2011a** (NE)**, Samy and ElMaraghy 2012b** (CS)
State of machines	**Kuzgunkaya and ElMaraghy 2006** (CS)**, Samy and ElMaraghy 2012b** (CS)
No of buffers	**Kuzgunkaya and ElMaraghy 2006** (CS)**, Samy and ElMaraghy 2012a** (CS)**, Samy and ElMaraghy 2012b** (CS)
Type of buffers	**Kuzgunkaya and ElMaraghy 2006** (CS)**, Samy and ElMaraghy 2012b** (CS)
State of buffers	**Kuzgunkaya and ElMaraghy 2006** (CS)**, Samy and ElMaraghy 2012b** (CS)
Failure	**Kuzgunkaya and ElMaraghy 2006** (CS)**, Samy and ElMaraghy 2012a** (CS), **Zhang and Tseng 2007** (CS)
No of processes	Sivadasan et al. 2002 (S), **Garbie and Shikdar 2011b** (CS)**, Garbie and Shikdar 2011a** (NE), Blecker and Abdelkafi 2006, **Deshmukh, Talavage, and Barash 1998**

	(NE), **Jacobs 2013, Schaffer and Schleich 2008** (CS), **Sivadasan et al. 2006** (NE)
No of production lines	**ElMaraghy et al. 2012, Wang et al. 2011, Kuzgunkaya and ElMaraghy 2006** (CS), Sivadasan et al. 2002 (S), **Garbie and Shikdar 2011b** (CS), **Garbie and Shikdar 2011a** (NE), Blecker and Abdelkafi 2006, **Deshmukh, Talavage, and Barash 1998** (NE), **Perona and Miragliotta 2004** (CS), **Schaffer and Schleich 2008** (CS), Hayes and Clark 1985
Manufacturing strategy	**Garbie and Shikdar 2011a** (NE), Blecker and Abdelkafi 2006, Wiendahl and Scholtissek 1994, Isik 2009
Resources	**Garbie and Shikdar 2011a** (NE), **Deshmukh, Talavage, and Barash 1998** (NE), **Zhang and Tseng 2007** (CS)
Job shop	**Deshmukh, Talavage, and Barash 1998**) (NE), **Zhang and Tseng 2007** (CS)
Capital costs (rent/heating)	**Perona and Miragliotta 2004** (CS), **Zhang and Tseng 2007** (CS)

The table above describes all the CCFs that are related to production. This group of processes gathers the majority of the factors, which are related to the machines and the production flow, batch sizes, change-over and set up times, but also to the assembly processes, tools and operators. It is worth mentioning that there is a high commonality (2/3) between the list of the factors that are relevant to the number of components and the list of the factors relevant to the number of finished goods. Moreover, there is information about the quantification of all the CCFs for the production and manufacturing processes and the majority is supported by empirical evidence, specifically case studies.

Table 4 - Articles discussing “Manage logistics and warehousing”

	No of components

Transportation and handling within the production site and warehouse	**ElMaraghy et al. 2014** (CS)**, Garbie and Shikdar 2011a** (NE)**, Deshmukh, Talavage, and Barash 1998** (NE)**, Samy and ElMaraghy 2012a** (CS), Isik 2009, **Zhang and Tseng 2007** (CS)
Product assortment in inventory	**Thyssen, Israelsen, and Jørgensen 2006** (CS)**, Jacobs 2013**
Scrap	**Perona and Miragliotta 2004** (CS)
Location of warehouses	Hayes and Clark 1985
	<u>*No of finished goods*</u>
Product assortment in inventory	**Li 2007** (NE), Sivadasan et al. 2002 (S), **Perona and Miragliotta 2004** (CS)**, Jacobs 2013, Benjaafar et al. 2004**)
Warehouses	**Garbie and Shikdar 2011b** (CS)
Inventory	**Garbie and Shikdar 2011b** (CS)**, Perona and Miragliotta 2004** (CS)**, Foster and Gupta 1990** (CS)**, Benjaafar et al. 2004, Blecker et al. 2004**
Transportation and handling within the production site and warehouse	**Garbie and Shikdar 2011a** (NE)**, Deshmukh, Talavage, and Barash 1998** (NE)**, Perona and Miragliotta 2004** (CS)**, Samy and ElMaraghy 2012a** (CS), Isik 2009, **Zhang and Tseng 2007** (CS)
Identification system	**Garbie and Shikdar 2011a** (NE)
Scrap	**Perona and Miragliotta 2004** (CS)
Administrative costs	**Rommel et al. 1993** (CS)**,** Wiendahl and Scholtissek 1994

*Table **4*** gathers the CCFs identified in the process of storage and distribution. The factors describe the activities of keeping components and finished goods in stock, but also handling activities within the warehouse and the production site and location of the warehouse. Moreover, the volume of the inventory and the scrap rate are described as factors that cause asymmetrical cost distribution. The identification system of the finished products that are kept in stock and the maintenance of it via administrative tasks are discussed as factors responsible for costs that are uneven among the products. All the CCFs related to distribution and warehousing from the literature study, except for the factor “Location of warehouses”, are accompanied with quantification examples and supported by empirical evidence. The CCF “Location of warehouses” is only discussed without any quantification method or empirical evidence.

Table 5 - Articles discussing “Markets, customers, and capabilities”

	No of components
No of orders	**Thyssen, Israelsen, and Jørgensen 2006** (CS), **Perona and Miragliotta 2004** (CS), Isik 2009, **Bozarth et al. 2009** (S), **Sivadasan et al. 2006** (NE)
Order size	**Perona and Miragliotta 2004** (CS), Cooper and Kaplan 1998, Isik 2009, **Bozarth et al. 2009** (S), **Sivadasan et al. 2006** (NE)
	No of finished goods
No of orders	Sivadasan et al. 2002 (S), Blecker and Abdelkafi 2006, **Perona and Miragliotta 2004** (CS), **Rathnow 1993** (CS), Wiendahl and Scholtissek 1994, Isik 2009, **Sivadasan et al. 2006** (NE)
Demand	Sivadasan et al. 2002 (S), **Garbie and Shikdar 2011a** (NE), **Deshmukh, Talavage, and Barash 1998** (NE), Isik 2009, **Sivadasan et al. 2006** (NE)
Information flow	Sivadasan et al. 2002 (S), Isik 2009
No of customers	**Garbie and Shikdar 2011b** (CS), **Perona and Miragliotta 2004** (CS), **Rathnow 1993** (CS), **Sivadasan et al. 2006** (NE)
Order size	**Perona and Miragliotta 2004** (CS), Cooper and Kaplan 1998
Order taking process	**Blecker et al. 2004**

The last table presents the factors related to the sales process. All the factors listed above, both regarding the number of components and the number of finished goods, are internal factors that are related to complexity. Even though some of them are related to the customers and the sales processes, as discussed in the relevant literature, these factors refer to the capabilities of the company. Consequently, they are considered to be responsible for the uneven cost allocation among the products. “Information flow” is the only factor without any quantification methods discussed in the literature and the CCF “Order taking process” is not supported by empirical evidence. The rest of the CCFs identified are supported both by quantification examples and empirical evidence (case-studies, numerical examples, surveys).

As it can be seen from the tables above, the identified CCFs are related to both the number of variants on finished goods level and number of components. Specific process steps identified are the flow of materials, variety in the production lines, machinery, warehouse and distribution, customers’ service and order handling process. In detail, batch size, set up time, waiting time, tools and flow shops are the main factors related to production and machinery. With reference to supply, CCFs identified are number of customers and number of distribution centers. Logistics and warehouses gather also various CCFs, such as number and size of warehouses, locations, capacity, variability of inventory and handling processes in the warehouses. Through these factors complexity costs can be quantified.

It should be mentioned that in the literature review, some of the CCFs are quantified or/and tested in cases. In addition to that, the level of detail, regarding the quantification method and the data required vary significantly among the different articles. However, these two aspects (quantification methods and data acquisition) are not considered in this current work.

3. Research methodology

This paper examines the existing literature on identification of CCFs. Firstly, the various approaches of analyzing complexity by academia and practitioners are examined and discussed. Then, the factors for quantifying complexity, both from the literature and the case studies, are identified and then categorized. Therefore, an integrated framework, linking complexity in both products and processes is used, and is built upon the industrial standard for process classification, in order to enable classification of the CCFs. The identified CCFs from the literature are tested in case studies. The outcome of this research aims to identify which CCFs are most relevant for the case companies. In addition to that, for the CCFs identified in the case companies are analyzed and quantified. The actions taken based on the analysis and the impact on reducing complexity costs are further discussed and evaluated, along with the insights gained from each application of the complexity management theory.

Case research is the method selected for this work as it allows to study the phenomenon in its natural settings and addresses questions of why, what and how (Meredith 1998). The purpose of this research is to test the theory regarding identification of CCFs. In order to do so, the key variables have to be identified, the relationships among the variables have to be defined and explained (Voss, Tsikriktsis, and Frohlich 2002). For that reason, multiple focused case studies (7) have been used and researched in depth; each of them is considered to be highly representative in its field of operations.

Based on these, the following proposition has been formulated and tested in the case studies:

Proposition 1. Which CCFs identified from the literature may be used to identify and quantify complexity costs in a manufacturing company?

Seven companies have been used as case studies. Each company has been researched for a 5 month period, so that it would be possible to collect and analyze the required data. In all cases, CCFs were identified and evaluated. This in depth analysis allows relatively high validation of the acquired information (Yin 2013). Then, the CCFs identified in the case-studies are also classified in the framework.

The APQC industrial standard is used for that purpose (APQC 2015). Since this classification framework describes all the processes in an industrial environment, it can be applied to all the companies examined. The purpose of categorizing the CCFs under the APQC framework is to enable a cross-examination and comparison among different manufacturing industries and allow for generalizability of the research method. This categorization also serves a direct comparison between the factors discussed in the literature and those identified in the case-studies.

4. Case studies

In order to test the factors identified and provide empirical evidence, the complexity costs have been analyzed in seven manufacturing companies by applying the relevant factors. All companies are in the manufacturing industry and produce standard products to stock. The companies produce different products and differ in size. The reason for selecting these companies with such diversity is to compare the CCFs across organizations and to get a better understanding in tandem with setting the limitations of this research.

The selected companies vary in size and type of products they manufacture. The unit of analysis is the set of final product variants that the companies offer to their customers. In order to ensure consistency among the different cases, all data is obtained from the ERP systems. The data is also discussed with the project managers, so as to certify that the research team has all the information needed and that the data acquired is up-to-date. Moreover, a research protocol is developed and followed in all cases, regarding data retrieval and processing, in order to ensure external validity of the research. The following table provides an overview of the CCFs identified in each case. After each CCF, if identified in a case, the ID of the company follows (e.g. A, B, C etc.). When quantified, the ID of the company appears in bold.

Table 6 - Categorization of CCFs in the case-studies under the APQC standard

Product/ Process	CCF	No of components	No of FG
Plan for and align supply chain resources	Material flow pattern	-	D
Procure materials and services	No of suppliers	**G**	**G**
	Cost of sourced components	**-**	**C**, D
Produce/ Manufacture/ Deliver product	Operator	E	E
	Capacity utilization	**F**	**F**
	Set up	D	**-**
	Changeover	E, **F**	**-**
	Batch size	**E, F, G**	**-**
	Capital costs (rent/heating)	G	D, E, G
	No of production lines	-	D
	Manufacturing strategy	-	D
	Resources	-	D, E
Manage logistics and warehousing	Transportation and handling within the production site and warehouse	**B,** G	**A,** D, **E,** G
	Product assortment in	**A, B, C, D, F, G**	**A**, B, **C, D, E,**

	inventory		**F, G**
	Scrap	G	A, **E,** G
	Location of warehouses	D	**-**
	Administrative costs	**-**	A, **D**
	Freight	**-**	**A, D**
	Insurance	**-**	**E**
	Shelf-life	**-**	G
Markets, customers, and capabilities	No of orders	**A**	**A**
	Order size	**A**	**A**
	Demand/Sales	**-**	**A**
	Order taking process	**-**	B, **D, G**

As it can be seen from the table above, CCFs identified in the case-studies cover the same business processes as from the literature review. The main limitation to this research is the availability and validation of the data acquired. For that reason, the research team was not able to quantify all the CCFs identified. The most frequent CCFs identified and quantified, both from the literature review and the empirical evidence, are the product assortment that is kept in stock and the transportation and handling within the production site and warehouse. Nevertheless, there is no pattern identified regarding which CCFs are found in each case and if they are connected.

After identifying the CCFs and quantifying complexity costs, several initiatives have been developed and evaluated for each of the cases regarding complexity reduction and control. Since the identified factors are different for each case, the scenarios developed vary but are developed based on two main concepts: product complexity (e.g. reduction of variants Suzue and Kohdate [1990], Jiao, Simpson, and

Siddique [2007]) and process complexity (e.g. optimization of the production process Ramdas [2009], De Groote [1994]).

In detail, reduction of product complexity is a suggestion applied to all the case companies. This scenario is implemented through a number of different initiatives such as reduction of product range, elimination of variants, standardization of the portfolio, reusability in product design and substitution on both finished good and component level. Regarding process complexity, the initiatives implemented to the case companies are process optimization, distribution of products and inventory management.

The following table (Table 7) illustrates the results from the identification and quantification of the CCFs in the case studies, the scenarios suggested for reducing and controlling complexity and their impact. In the last column, the impact of the suggested actions to reduce complexity is quantified. Based on the availability of the data acquired in each case study, the impact is measured as Earnings before interest, taxes, depreciation and amortization (EBITDA), Contribution margin (CM), calculated as the difference of the net revenue minus the direct cost (Farris et al. 2010), Contribution ratio (CR), calculated as the percentage of the CM divided by the net revenue. In order to allow comparison among the different case companies the unit of the impact is in million Euro (m€).

Table 7 - Complexity management in case studies

Company Product No of variants	**Factors quantified**	**Actions**	**Impact**

A **Medical devices, sensor cassettes** 120	o Transportation and handling within the production site and warehouse o Product assortment in inventory o No of orders o Order size	o Adjusted portfolio based on different properties of the product lines, not the individual products, reduction by 28% of the products offered o Process optimization, capacity improvements and shift model, new factory	o Discontinuing 35 variants increases EBITDA to 27,2 m€ o New capacity strategy increases EBITDA by 25,1 m€ in 6 years (current 165 m€)
B **Pumps** 2736	o Transportation and handling within the production site and warehouse o Product assortment in inventory	o Reduction of the product range o Standardization of the portfolio	• 4,3% cost reduction and 18% CM increase by merging 36 products (12% of portfolio)
C **Anlytical instruments** 40	o Cost of sourced components o Product assortment in inventory	o Product portfolio management o Increase standardization and reusability in product design o Inventory costs reduction	o 24% reduction in material cost (1,8 m€) o 30% reduction in inventory cost (0,32 m€)
D **Commercial electrical appliances** 350	o Product assortment in inventory o Administrative costs o Freight o Order taking process	o Elimination of C items – No substitution o Elimination of C items – 100% substitution o Elimination of C & B items – No substitution o Elimination of C & B items – 100% substitution	o Scenario 1: 2,1% CR increase o Scenario 2: 1,3% CR increase o Scenario 3: 1,9% CR increase o Scenario 4: 1,2% CR increase

E **General Building Insulation products** 175	o Batch size o Transportation and handling within the production site and warehouse o Product assortment in inventory o Scrap	o Decrease product assortment o Increase substitutability	o Total savings after both scenarios 20-25 m€ (8-11%) of EBITDA 236 m€
F **Mattresses** 3714	o Capacity utilization o Changeover o Batch size o Product assortment in inventory	o Product substitution (scenario 1 & 2) o Process optimization (scenario 3)	o Warehouse capacity optimization by 11,3% o Component reduction by 31,4% o Savings from process optimization 0,25 m€
G **Frozen food** 666	o No of suppliers o Batch size o Product assortment in inventory o Order taking process	o Decrease product range o Decrease no. of suppliers o Inventory management	o Remove 15% of the products , which are unprofitable, and increase EBIT by 0,05 m€ o Savings by product substitution 0,2 m€ o Increase profit 0,09 m€

In each of the under examination case studies, the scenarios for complexity elimination are related to the factors identified. For example, in the case of company C the CCFs identified are cost of sourced components and product assortment in inventory. Based on these, the suggested initiatives include standardization in product design in order to increase reusability of components and parts used in the finished products. The second initiative addresses the cost of keeping both components and finished goods in stock and it suggests keeping in stock products and components used in products that are high sellers, since they spent less time in the warehouses, they do not become outdated or obsolete and this leads to decreasing the cost of inventory.

As mentioned above, one of the most frequent CCFs identified and quantified both in the literature study and in the case studies, is the product assortment in the inventory. In the case companies that this CCF is identified the suggested actions include component and product substitution as an immediate action to reduce product and process complexity. For the products that are producing no profit, complete elimination is also one of the actions taken (Wilson and Perumal 2009). Additionally, the standardization of the product platforms is suggested as a long-term measure in order to increase reusability of parts and components in the finished products. Reducing the product complexity leads to reduction in process complexity. By looking into the same example of the CCF of the product assortment in inventory, we can see from the case studies that the reduction in the number of parts or finished goods that are kept in stock has a direct effect on capacity optimization of the storage space, the production lines and the overall cost.

Regarding the impact from each of the suggested actions in the case-studies in order to tackle product and process complexity, there is a variation, as it can be seen in the last column of *Table **7***. Another issue that is identified by comparing the impact in the different case-studies is the fact that due to data availability and verification in each company, the impact is quantified using different methods and indexes. For instance, in company A and E the impact is quantified by using the EBITDA, while in company D is presented as a percentage of the CR. At last, another lesson learnt from the case studies is that even companies with relatively smaller product assortment can also benefit from reducing underlying complexity costs. For example, by comparing the results from the companies B and C in *Table **7*** we can see that company C has 40 product variants while company B 2736 product variants, yet product complexity is still identified and by implementing initiatives to control and reduce complexity the impact is worth mentioning.

5. Discussion and Conclusions

This research focuses on identifying and categorizing CCFs from the literature review and the case-studies under the APQC framework of process classification. Product complexity, measured in terms of number of components and number of finished goods, causes complexity to several process steps. By comparing the results from the literature review and the empirical evidence regarding product complexity, it can be seen that CCFs related to material handling systems have not been identified in the cases, as well as factors related to machines, buffers and tools. On the contrary, in almost all cases have been identified and quantified CCFs in processes related to inventory, production and sales. In detail, CCFs related to the process group of logistics and warehouse, such as freight costs from the warehouse to the distribution centres, insurance costs of finished goods and their shelf-life have been identified and quantified in some of the cases, but not in the literature. This, points out the need of extending the literature research.

Factors related to markets and customers have been identified in the cases, yet not quantified. The same applies for material flow, where the lack of data did not enable the research team to quantify the complexity costs. The lessons learnt from the empirical evidence are discussed.

Summarizing the findings from the literature and the empirical evidence in order to answer the proposition, the most common CCFs discussed in the literature and identified in the case studies are related to the number of components and variants kept in stock, machine utilization, batch sizes and changeover times. Furthermore, processes related to supply, logistics and distribution gather also numerous factors. In detail, transportation and handling within the production site and warehouse, number and size of orders, and number of suppliers are the "usual suspects".

In overall, it can be seen that the factors discussed in the literature align with the factors identified in the case-studies. Additionally, the use of the APQC framework and the classification of the CCFs allow for cross-examination not only between the literature and the empirical evidence, but also among different companies.

5.1 Future research

The results indicate that the complexity in products, described by the number of components and finished goods, are the source of increasing complexity in processes, such as production and delivery. This research is a stepping stone in order to develop a concrete framework for managing complexity in the manufacturing sector. Data acquisition and validation, quantification methods and methods for application of the CCFs classification in different industries are future research fields.

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ARTICLE H

Managing complexity of product mix and production flow

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Managing complexity of product mix and production flow

Abstract

Purpose – This paper studies the relationship between product portfolio complexity, production flow and inventory optimization in assembly-to-order production systems. It investigates the effect of component substitution on lot sizing and capacity utilization, while maintaining the production capacity as well as the external product variety.

Design/methodology/approach – The examined methodology is built upon the theories on ABC product categorization, variant and component substitution and capacity utilization of machinery and stock. A research protocol demonstrating the data required and the quantification steps is developed to allow replication of the research design. In order to test the suggested approach a case study of an assembly-to-order manufacturer is conducted.

Findings – In designing assembly-to-order production systems for a growing product variety, companies are challenged with an increased complexity for obtaining high productivity levels and cost-effectiveness. The case study verifies the relation between product mix and production flow. It further quantifies the positive impact of a simplified portfolio on machine utilization and inventory capacity.

Originality/value – In academia several optimization methods and conceptual frameworks for substituting components, or increasing lot sizes and storage capacity have been proposed. This study presents a general framework for quantifying the impact of a two-way substitution at different production stages and its impact on storage and machinery utilization. The empirical evidence verifies the introduced methods and confirms the supporting theories.

Keywords Complexity management, Assembly-to-order, Inventory control, Variant substitution

Paper type Research paper

1 Introduction

The ability to diversify product portfolios while sustaining a low level of operational complexity is seen as a major challenge many manufacturing companies are facing nowadays (Jacobs and Swink, 2011). In order to obtain a competitive advantage, organizations have reacted with a significant expansion of product variants to the market, causing an inevitable complexity in product architecture, assembly and supply process (Hu et al., 2008). Principles like mass customization have been reported to facilitate bridging the gap between the need for product differentiation and market responsiveness (Salvador and Forza, 2004). From a supply chain perspective, postponing the customer order decoupling point towards an assembly to order (ATO) production system helps to deliver individual product variants with a relatively high production efficiency (Salvador et al., 2004). In an ATO production environment the product differentiation can take place on different levels of assemblies, from sub-modules to final assemblies. Through modular product design production steps can be divided into a set of intermediate and interchangeable sub-assemblies, thereby distributing the operational activities into smaller easier to handle tasks (Prasad, 1998). Yet, recent research has shown that the merely increase in product variety with modular design is no guarantee for an increased profit, as product variants typically contribute unevenly to the net revenue of the company (Wan et al., 2012).

The profitability of each product variant is tightly coupled to its manufacturing and is often related to the production flow, in terms of lot size and Stock Keeping Units (SKUs) (Yücel et al., 2009). One of the suggested approaches to assess the impact of the increasing product mix on the firm's performance is to investigate how variety complicates the assembly process and supply chain operations (Braglia et al., 2006).ElMaraghy and Urbanic (2003) introduce two factors of increasing variety induced complexity, firstly the number and diversity of features to be manufactured, assembled and tested, and secondly, the number, type and effort of the tasks required to produce the features. Yet traditional production and inventory planning related research has concluded to an integrated model optimizing the values for the process mean, quantity, and production lot size (Al-Fawzan and Hariga M., 2002). While both aspects are relevant when investigating the impact of increasing product differentiation, their interrelated impact has seldom been discussed. This research therefore studies how both reducing product portfolio complexity as well as increasing production flow and inventory utilization can contribute to the overall performance of manufactures offering custom tailored products.

The remaining paper is structured as follows: After having introduced the research topic, section 2 discusses the related literature and builds the conceptual framework for the proposed approach. Section 3 substantiates the research aim and methodology, while in section 4 describes the results from testing the suggested approach on a case study. Finally, a conclusion of the research outcome is given in section 5.

2 Theoretical Background

2.1 Product complexity and architecture

The concept of complexity has been studied from various perspectives. In engineering domains, term is generally related to the design of product architectures and the commercial variety created through them (Martin and Ishii, 2002). With product architectures, engineers create an abstract representation of a product design. They express how product functionality is realized by a set of interacting physical components and their formally expressed interfaces (Ulrich, 1995). By rearranging the structural characteristics and adding optional components to the architecture, the design of the product and its variety can be altered. In industries with higher needs for customization, this rearrangement can play an essential role the economical success of a product (Pil and Holweg, 2004). Since high product mixes tend to require an increase number of components and interchangeable options, the design and handling of such products can be a challenge (Veldman and Alblas, 2012). Measures defining the resulting complexity are diverse and typically emphasize either the product design or its handling. Product oriented complexity measures focus on the structural characteristics of the product architecture, i.e. number of components and the nature of their relationships (Sosa et al., 2007). A way to limit the resulting complexity is to increase the amount of common components across variants in a reusable platform and by introducing interchangeable modular options (Erens and Verhulst, 1997).

Alternatively, complexity can be studied from the perspective of organizations and the way they deal with complexity. Samy and ElMaraghy (2012) for example define complexity as degree to which product variety can complicate the production process. In the same concept, Arteta and Giachetti (2004) point out that complexity is preventing a company from changing its organizational structure, processes and products, and is connected to the interrelationships of the system elements. MacDuffie et al. (1996) quantify product complexity to test the impact of product variety on quality and productivity in a LEAN manufacturing environment. Several researchers have performed similar work (Fisher and

Ittner, 1999; Fujimoto et al., 2003; Martin and Ishii, 1996) where the focus has been to measure how the production process is affected by product complexity, related to the increasing number of variations. An approach widely used for measuring organizational complexity seen as a system consisting of the interplay between products and processes is based on entropy measure (Arteta and Giachetti, 2004). According to the authors, system complexity arises not only from components and their interrelations in a structure, but also from the emergent change of these relations, caused by different states of available material and information flow. To cope with the dynamical element of complexity, these different states are assigned probability measures.

Lot size and demand are also factors related to product and process complexity. To this end, Masuchun and Masuchun (2008) have created a model to determine the optimum lot size in order to match the production flow and the customers' demand. Bottleneck machines affect the production rate, and in order to maximize efficiency the lot size should be large (Koo et al., 2009). Furthermore, Yu (2012) examines the production lot size in relation to the demand. Benjaafar and Gupta (1998) are suggesting that the number of final products and the lot size are commensurate, however they results are based on the assumption that the production facility is able to expand or change.

However, the focus of this article is on eliminating not value adding complexity. Complexity is often related to variety and profitability. Profitability varies greatly among products and product families and that could be an indication of which products are positively contributing to a company's performance. As a result, the analysis of products profitability is required. In order to determine this, the ABC product classification method is used.

2.2 ABC product classification

The ABC analysis was initially introduced by Pareto (Pareto, 1971) and has been further used in operations management domains. It categorizes products into A, B, and C based on the relative distribution of cost or the usage of the SKUs.

With the rapidly increasing number of variants in the recent years, manufacturers are trying to maximize the variants offering, in order to serves their customers' needs, increase competiveness and identify the market niche. However, not all variants contribute to the net revenue neither at the same percentage. As a result large product variety does not imply for stable long-term profitability (Koo et al., 2009; Liiv, 2006; Sarkis, 1997), and the ABC product differentiation becomes imperative. The ABC product prioritization can include a number of additional aspects, which have been of great importance for inventory management within operations management domain, such as lead time, substitutability and variability (Benito and Whybark, 1986). Recent studies have shown relations between the ABC product differentiation and the lot size (Yücel et al., 2009) or substitution (Hsu et al., 2005).

2.3 Substitution methods

Substitution is a method which complies with Mass customization principles and platform designs. Garud and Kumaraswamy (1995) describe as "*economies of substitution*" the manufacturing strategy that companies apply, regarding reusability of components within a company's product range. Ye (2014) categorizes substitution into two classes: vertical and horizontal (Figure 1). Vertical substitution can be one-way, where the product of higher quality or value can substitute a product of lower quality or value (Hsu et al., 2005; Smith and Agrawal, 2000), or two-way, where products of both higher and lower can substitute each other (Xu et al., 2011). Horizontal substitution can be distinguished between centralized and decentralized. Current research refers to this classification as firm-driven (centralized) and customer-driven (decentralized). This research is primarily focus on two-way firm-drive substitution at a module level, as the customer-driven substitution cannot be controlled. The sales person, or even the customer himself, decides on the substitution of one final product with another (Zhou and Sun, 2013).

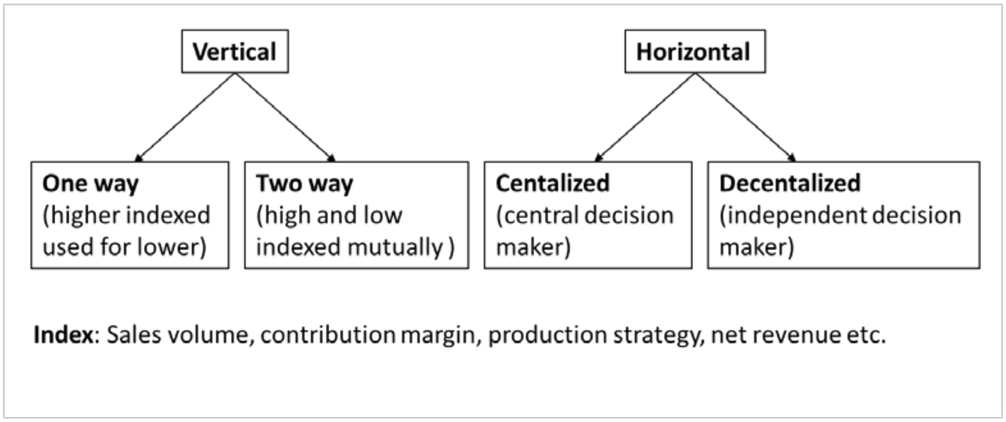

Figure 1 - Substitution categorization

Zhou and Sun (2013) have developed a model to determine the optimal component quantities in an assembly-to-order system with component substitution, so as to maximize manufacture's profitability. They consider firm-driven component substitution due to lack of inventory and production cost, distribution cost and revenue loss are the parameter to be taken into account. Rao et al. (2004) develop a model to estimate the specific products to be produced, their quantities and how these products can satisfy the demand. Costs that are taken into consideration in the model cover setups, production, overage, stock out and substitution. This refers to one-way downward substitution, where the demand of a certain product can be satisfied by a specific range of products. The impact of product substitutability on optimal capacity and flexibility is discussed by Lus and Muriel (2009), where they also consider pricing, as aspects to be taken into account when planning the product assortment.

Several researchers have considered product substitution based on the demand. Yaman (2009) creates a model in order to define the lot sizing problem by substituting the products of low quality with high quality products. On the other hand, Hsu et al., (2005) develops algorithms in order to define the lot size between two products. The product in lower demand can substitute the product higher demand, with or without the need for redesign.

2.4 Research aim

Based on the previous literature review, this paper attempts to contribute to the quantification of the relationships between product complexity and lot size. The factors taken into consideration are product common features on module level, substitution on component level and lot size determination. Drawing upon the basic idea of mass customization, we present a concept where the final product variation is not to be decreased and for short and mid-term planning the production facility is considered under the limitation of neither expansion nor change. The ABC categorization approach is used to determine the appropriate components' substitution strategy, as well as the lot sizing.

The purpose of this paper is to examine the production flow optimization by adapting the product assortment. The previous research has shown the dependencies between the two aspects, however in this paper we examine them from another perspective. The product mix is our variable, while the production flow is kept fixed. Due to limitations on expansion of stock and number of machinery, the impact of the product assortment adjustment is used to measure productivity. Additionally, production size should not be affected.

Proposition 1 (P1)

Substitution on a module and component level contributes to improving of the production flow and capacity utilization of machinery and inventory.

3 Research Methodology

Based on a literature study, the paper first examines the interrelation between the product mix and the production flow in terms of complexity. Mass Customization principles are highly related to the dependency between complexity management and profitability optimization (Zhang and Tseng, 2007). Blecker et al. (2004) suggest analyzing the interrelation between product variety and process domain. In order to create an understanding of their relative importance with respect to the area of complexity management, a case study of a manufacturer offering assembly-to-order (ATO) products is performed. The company is selected as it is a highly representative example of an ATO manufacturer that applies mass customization techniques. Furthermore, the restrictions of this manufacturer enable the research team to fully test and evaluate the suggested method as the environment of the selected case sets the constraints that are taken into account in the under examination proposition.

Case study is selected as the research method for this work, as it allows the research team to study the phenomenon in its natural settings (Benbasat et al., 1987). Additionally, case research is suitable for exploratory studies, as it allows deeper understanding of the relations among the variables and phenomena that are not fully examined or understood (Meredith, 1998).

In theory testing, case study research allows defining the set of variables, their relationships and predicted outcome (Wacker, 1998). In this research study the under examination construct is component substitution. The predicted outcome is optimization of the process flow and machine utilization. The degree of control of the research team during the process is relatively high when conducting case research, by having the flexibility and possibility to go back for additional data or clarifications required, while it is low regarding the outcome, when the researcher is obliged to keep distance and observe the results without affecting them (Sousa and Voss, 2009).

However the various benefits of applying case study research there are several challenges and limitations. The researcher must be unbiased during data collecting and analysis, as well as not to have an effect on the informants, in order to ensure internal validity (Sousa and Voss, 2009). Secondly, case research is time consuming and it requires skilled interviewers, in order to result in a rigorous research (Voss et al., 2002). Finally, in this research study, as it is based on a single case, generalizability of the conclusion is limited. In order to ensure the external validity, the research protocol and research design are developed and discussed into detail for allowing further theoretical and literal replication of the study.

Based on the research methodology discussed in the previous section, the conceptual framework of this study examines the relationships among component substitution, machine utilization and process flow.

The data sample regards all product orders and the related daily activities in machine and inventory utilization for a one-month period. The research group followed the principle of triangulation in collection of data, by using different methods (unstructured interviews, direct observations, content analysis of documents and archival research) to study the phenomenon (Voss et al., 2002). Data collection is performed through the ERP system and data verification via experts of the company. The product manager was involved in the project as a key person from the company, in order to verify the data collection. For that reason, unstructured interviews were performed, as the product manager was involved in the whole process. On-site observations along with empirical data were gathered on a daily basis for one-month period and the forecasted increased demand in a two-year time period. The data sample regards all product orders and the related daily activities in machine and inventory utilization. Data collection included also the modular structure of the products in terms of assembly processes and stock capacity utilization. The following table summarizes the data required for the analysis.

Table 1- Research Protocol

Data needed	Quantification
1. **Bill of material of finished products** **Sales volume of finished products** **Net revenue of finished products** **Contribution margin of finished products**	Portfolio analysis ABC analysis on the component level Substitutability on the component level
2. **Average lot size per run per component** **Production per run per component** **No of batches per run** **Average batch size** **No of shifts** **Process time**	Process analysis Machine utilization ratio Calculation of the optimal relation between lot size and machine utilization
3. **Number of pallets with C components in stock** **Number of pallets with A components in stock**	Stock utilization caused by substituting C components with A components

The research protocol is developed in order to allow replication of the research and ensure external validation. The unit of analysis is the processes within the existing production set up. This in depth analysis follows the proposed methodology and hence allows relatively high validation of the acquired information (Yin, 2013). The method is used in order to argue and justify the causal effects of the variables and the results of the study. For that reason, the paradigm that this research lies upon is logical positivism (Karlsson, 2009).

3.1 Suggested approach

3.1.1 ABC product categorization

Based on the Pareto theory (Pareto, 1971), an ABC analysis on component level is performed, where the sales volume of finished products is used to differentiate between the categories. In detail, 80% of the sales correspond to fewer products, which are considered as A products. Similarly, 15% of the sales volume corresponds to the B products and 5% to the C products.

Sales values are often stored on a final product level. To be able to perform the ABC categorization on components level the variance decomposition structure is used. Each finished product is broken into its different components, based on the listed Bill-of-Material (BOM). The sales volume of the finished product indicates whether the product is A, B, or C. Through the variance decomposition analysis, the sales volume of the components is set in relation to the sales volume of the finished product.

The variant categorization is to be further used in order to implement the two-way substitution.

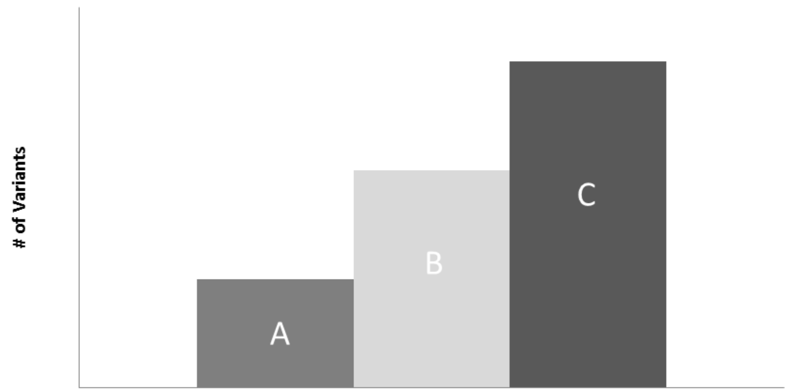

Figure 2 - ABC analysis on component level

3.1.2 Substitution and process flow

The second aim of the research methodology is to implement a substitution method in order to measure the impact on the machine and stock utilization, which is related to the lot size. The suggested approach is based on the theories discussed in the literature section; however it goes one step further by combining the substitution methods for which a two-way substitution method is proposed.

The first step of this method focuses on utilization of the C component variants kept in stock, in order to increase their utilization and free up the stock capacity. C components have by definition lower sales volume. They are taking up more space in the stock and for a longer time period, than the A components, which are used frequently. Moreover the average lot size of the C products is small, which is related to increased changeover and set up times, implying for increased cost and complexity in the production flow. The quantification of the stock capacity is calculated based on the average number of pallets occupied by each component in stock. The machine utilization is calculated on the number of components produced per run.

According to the suggested method, the C components kept in stock would replace the similar components in the A products. The main challenge is to identify which C variants could substitute the A variants in the final product assembly, without compromising neither the quality nor the specifications of the finished product. This first method can be seen a short-term suggestion, with a focus on achieving immediate impact in production

The second step of the substitution method proposes a long-term solution, in which the A components substitute the C components in the final product. This results in out phasing the C components of limited utilization, which leads to an increase of the stock capacity. At the same time the replacement of C components enables higher production and stock utilization of the A components, as manufacturers can plan with higher lot sizes. This action results in optimizing the machinery utilization, especially for those machines that are potentially creating bottlenecks. The optimization is succeeded by reducing the change overs and the setup times for producing A components. In relation to the stock capacity, the substitution of the C components has positive effects, as the slow moving pallets with C components are replaced by pallets with A components.

This step of the suggested approach identifies the relations between the substitution and changes in the lot size, and their impact on the production process.

3.1.3 Lot size and capacity utilization

The third step of the suggested approach, builds upon the previous and examines the relation between lot size and machine utilization. The reviewed theories indicate a connection between the lot size and the optimization of output of each machine in the production process. The bottleneck machines are of great importance in this stage. Additionally, the lot sizing is related to the second step of the substitution method (A components used for C variants). As the total volume of the A components increases, the manufacturer can plan with a higher average lot size of the process flow.

4 Case study

In order to test the proposed framework and quantify the production flow optimization by adapting the product assortment, a case study of a manufacturer in the CTO industry is performed. The company produces plaster gypsum boards for the construction industry. The final product consists of several layers (components): plaster façade (with or without paint), gypsum board, light reinforcement, heat and fire insulation. The challenging aspect of this specific case study is the lack of expanding options, especially on large scale such as expansion of the production site or the warehouse, purchase of supplementary machinery. There is limited available space in the production facility, which corresponds to a small machine or a new stock point for products in small volume. As a result the chosen case study is selected as an example where the optimization of production flow and capacity utilization could only be achieved by the examined proposition.

4.1 Complexity analysis at the current state

In order to implement and evaluate the suggested approach on this case study, the analysis of the current state is to be used as a baseline. The following figure illustrates the current production flow, with the bottleneck machines and stocks marked with grey.

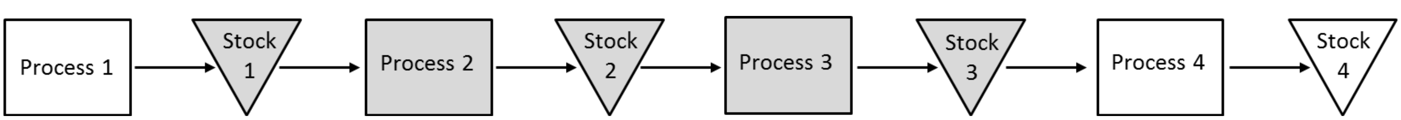

Figure 3 - Current production flow with bottlenecks

With reference to the production process, the products go through four machines. There are also four stock points, after each process. Based on the analysis of the data acquired, the production process was analyzed and the bottleneck machines were identified. The utilization ratio of each machine is used for that purpose, and is calculated by the following formula:

$$r_u = \frac{T_{projected}}{T_{theoretical\ available}}$$

The projected time refers to actual time that the machine was in use and is calculated as the sum of the queue time, set up time and process time. The theoretical available time is the total time for the shifts that are allocated for that specific machine. According to the production plan, each machine is running in three shifts per day. The utilization ratio is the percentage that enables to identify the machines that create the bottleneck in the production flow.

Based on the results all the intermediate stock points are exceeding the available capacity (see Figure 4, stock 1, 2 and 3), with utilization rate close to 100%, and in some cases up to 117%. The two machines operating the processes among these stock points (see Figure 4, process 2 and 3) have also utilization rate that exceeds 100% in 10 days out of 21 working days in the month the data refers to. As the focus of this study is to improve the production flow by optimizing the product mix and machine utilization, the next step is to analyze the products.

Implementing the suggested approach, an ABC analysis was performed to the finished products, and subsequently to the components. The following figure illustrates the relation between the volume of the finished products and the number of variants, based on the ABC product differentiation made after the related data was acquired. The data used for this ABC categorization is the net revenue from each and every product.

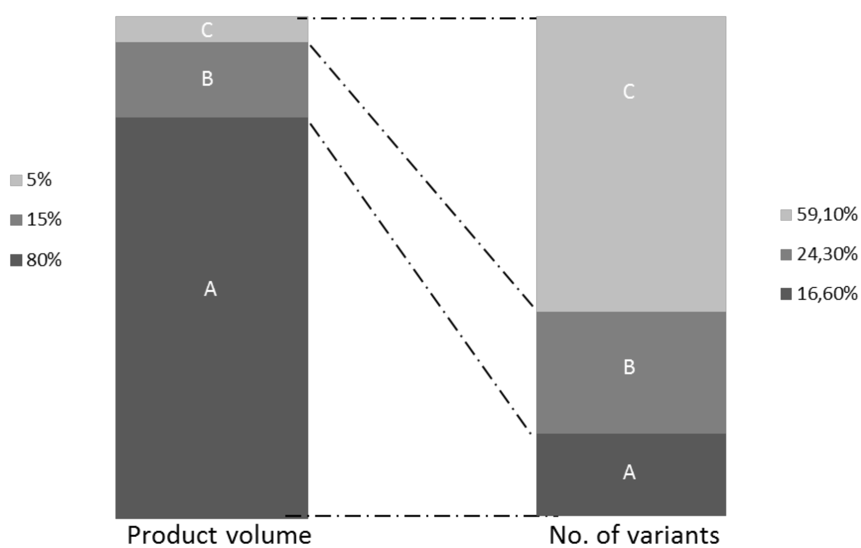

Figure 4 - Percentage of net revenue and number of product variants

Similarly, by relating the number of products to the contribution margin the result demonstrates that 80% of the contribution margin is generated by 16,4% of the products, which are categorized as A. the C products that create 5% of the contribution margin correspond to 59,1% of the product portfolio.

The results from the ABC categorization are presented in the following table. In order to categorize the products and the components as A, B or C the net revenue and the contribution margin were used. By applying the double Pareto law, the outcome of this grouping shows that only 17,4% of the products are generating high revenue, while the majority (60,9%) create the long tail (Wilson and Perumal, 2009) .

Table 2 - ABC product categorization

Product category	Net revenue [m€]	Contribution margin [m€]	No. of products	% of products
A	111,8	65	386	17,4 %
B	18,4	10,9	481	21,7 %
C	7,6	4,5	1351	60,9 %
Sum	**137,8**	**80,4**	**2218**	

The analysis of the current state constitutes the first step of the proposed framework. The historical data on sales volumes helps to estimate the current market trend and indicates in which steps of the production the capacity exceeds the maximum level, both in machinery and stock keeping units. The current state is used as a baseline scenario and serves when evaluating the alternative solutions.

In order to analyze the intermediate stock points, the following figure shows the average time for the A, B, and C components kept in stock. C components have in average 20 times more inventory time than A components. Due to this ratio, by eliminating C components the stock capacity will increase rapidly.

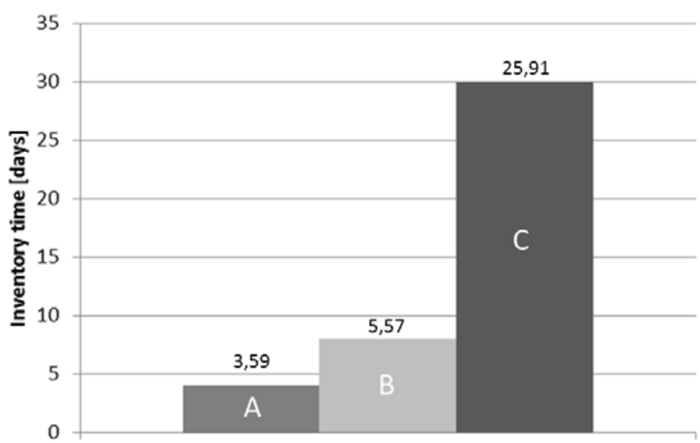

Figure 5 - Duration of components spent in stock per ABC component group

Additionally, based on the number of pallets in stock for each component, the following figure clearly illustrates that C componets require higher capacity, due to the fact that they are slowly moving. C componets take overall 43% of the available storage space.

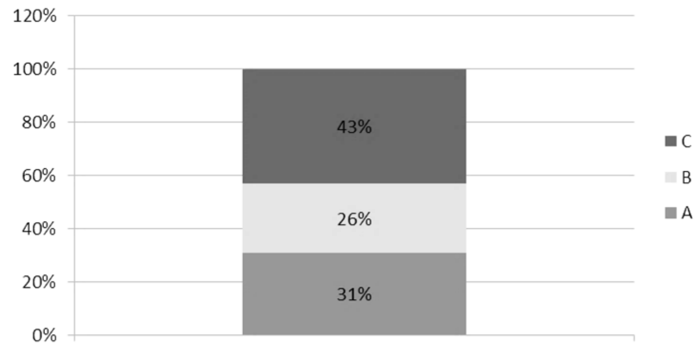

Figure 6 - Percentage of stock capacity occupied per ABC component group

With reference to the machines that also create bottleneck in the production process (see Figure 4, process 2 and 3), the following figures illustrate the production time lost due to changeovers in each machine. However the average utilization ratio of machine 1 is 82% and of machine 2 is 87%. This indicates that the machines' capabilities are not utilized to their maximum capacity, even though the production might be behind schedule, while some days they exceed their utilization ratio in order to keep up with the demand. This is due to the fact that the intermediate stocks have reached their maximum capacity limits; as a result they cannot accommodate the additional production volume.

In order to analyze further the machines in process steps 2 and 3 that create bottleneck, the changeover time is measured. The following two figures, figure 8 and 9, illustrate the average changeover time that is spent in every run for machines 2 and 3 respectively. The figures demonstrate the comparison among the time required for the different variants, A, B and C. It can be seen from the figures that the average times for B and C variants do not differ significantly from the average times of the A variants, even though the B and C variants combined correspond to 20% of the total net revenue. In detail, regarding the second process of the production flow (see Figure 7), the average total time that the machine is running is 6,2 hours. By combining the average time that is spent at changeovers for the B and C variants, it can be calculated that the 37 minutes required for the changeovers correspond to 10% of the total production capacity.

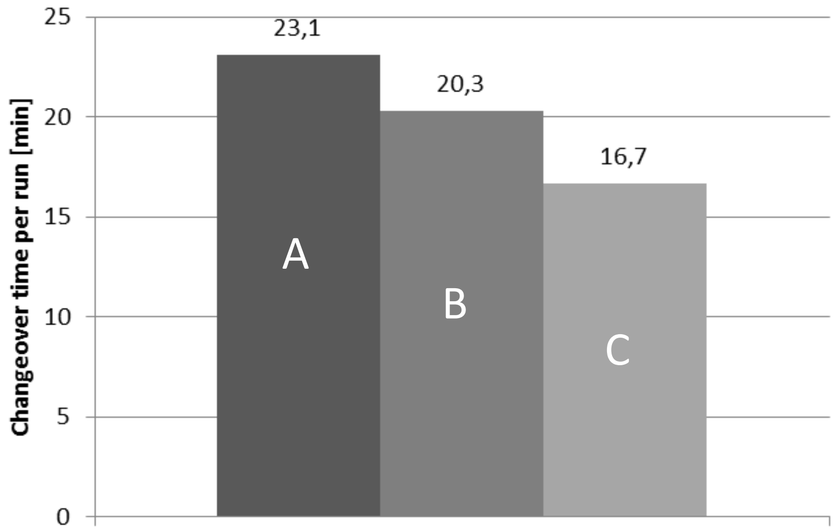

Figure 7 – Average changeover time per run per ABC variant group for process 2

Similarly for the third process (see Figure 8) the average changeover time for B and C variants combined is 35 minutes, corresponding to 9% of the production capacity for machine 3. This means that the B and C components, which are not the most profitable components that are produced, occupy the machine for 35 minutes to perform the changeover, while the A components have lower average changeover time for each run (12,1 minutes). The delays due to the changeover time contribute to the creation of the bottleneck in the process steps 2 and 3.

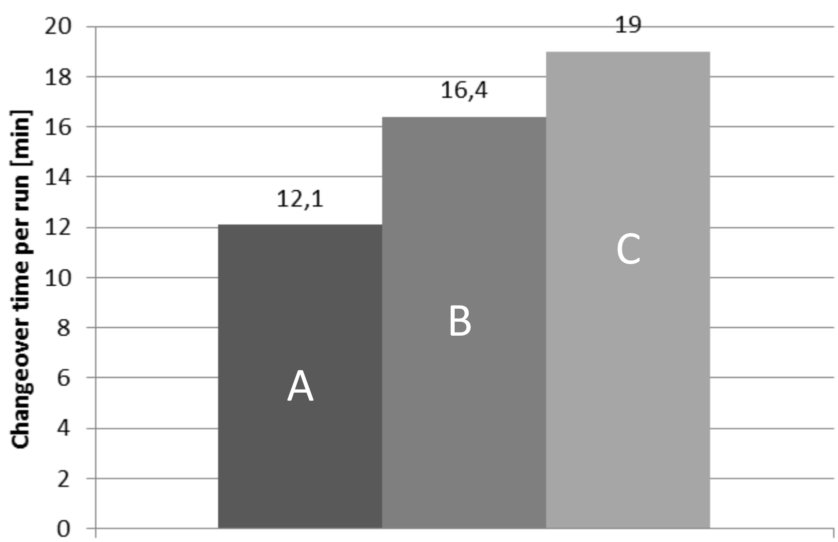

Figure 8 – Average changeover time per run per ABC variant group for process 3

4.2 *Suggested initiatives to reduce complexity*

4.2.1 Scenario 1

The first scenario suggests substituting C variants with A variants on component level, i.e. at an early stage of the production process. In our case study, the results from the early component variant decrease through substitution lead to a reduction both in stock capacity requirements, as well as in the bottleneck machines. This suggested solution has a direct impact on the first stock, by reducing the number of C products occupying capacity. By substiting the C components with A, the storage space will become available for A components, which will also lead to increase the production of A components.

4.2.2 Scenario 2

The second scenario consists of a combined short and long term solution, with two-way substitution at a later stage in the production process. The first step suggests the substitution of A variants by C variants, in order to reduce the number of the slow moving C variants in stock. This approach could be applied due to fact that the substitution will not jeopardize the quality of the final assembly, as for the case products the only difference between the two variants is the size of components (length, width). As a result the variation of the final products would not be affected. The effect of this solution can be realized in the released capacity of the second stock.

The second step of this scenario is the long term suggestion, which introduces substitution of C components on the final products by A. The substitution takes place at a later stage of the final assembly. The outcome of this scenario is a great reduction of stock capacity requirements, as the slow moving C variants are no longer produced. This strategy results in freeing up the space occupied by C variants and providing more space for the widely used A variants. The following figure illustrates the expected results from implementing the suggested approach. The current state is compared to the future state with and without implementing the recommendations.

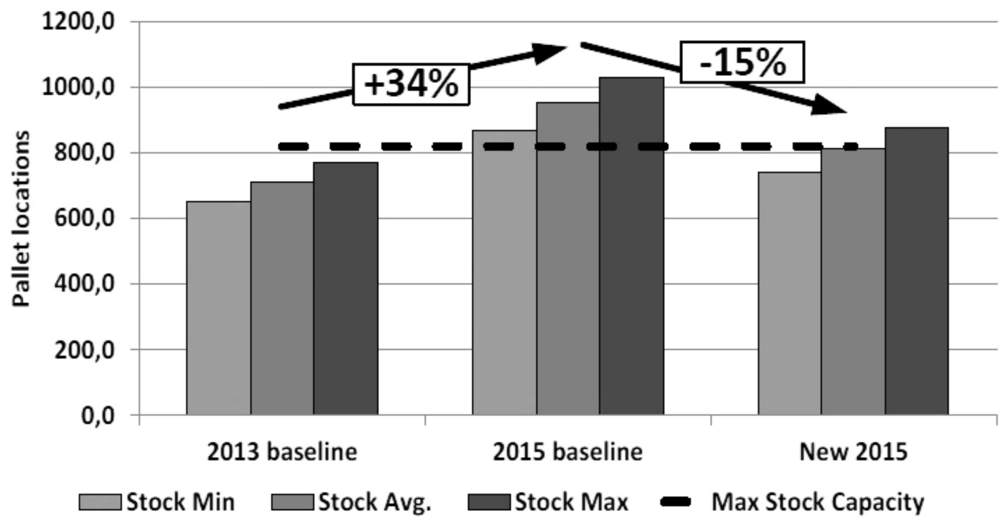

Figure 9- Capacity utilization improvement of the second stock

Furthermore, this solution targets the bottleneck machines. By eliminating the production of C components and replacing it with A components, changeovers are decreased and, subsequently, production time lost due to many changeovers can be used to improve machine utilization.

However, by substituting C components by A leads to an increased waste of material. The A components have bigger sizes than the C, so in order to apply the substitution approach, additional material has to be cut. This leads to extra scrap of approximately 2.680 Euro per year. This scrap is calculated by comparing the dimensions of the A components to these of the C components that are subjected to substitution. Taking into account this additional cost, the following table demonstrates the cost calculations for the implementation of the two-way substitution. The results of the aggregated approach reveal that regardless the extra scrap cost , the capacity optimization is improved by 11,3% free-up pallets and 31,4 % reduction of components is achieved.

Table 3 - Summary of substitution strategies

	C components for A product	**A component for C product**	**Both strategies**
Total no. of variants	618,8	618,8	618,8
Total no. of eligible C components	137,8	24,7	149,5
Total variants %	28,9 %	5,2 %	31,4 %
Total no. of pallets	83,93	14,97	92,70
Total pallets %	10,2 %	1,8%	11,3 %
Cost per pallet [€]	2.982,82	15.796,66	5.252,86
Total cost [€]	192.649,05	181.933,90	374.582,95

4.2.3 Scenario 3

The third scenario suggested builds upon the previous step of component reduction and increased storage capacity. In order to improve further the machine utilization, separation of the production and storage of the A and C components is suggested. Based on theory the output per run of a machine is increased as the batch size increases. This indicates that the production flow is to benefit from separating the production of C and A components by introducing a new machine that is devoted to the production of the C components and a separate stock before that. In that case, machine utilization will be improved for the high-run A components. For that purpose, the suggested approach includes the purchase of a new machine and the creation of a new stock, in order to allow the distinction of the production and stock of A and C components.

With reference to the machine utilization, the following figure illustrates the relation between the average lot size and the number of components produced per run. The tendency is quantified to the following formula:

Equation (1):
$y = 5{,}0433x + 123{,}36,$

where y corresponds to the number of components produced per run and x to the average batch size.

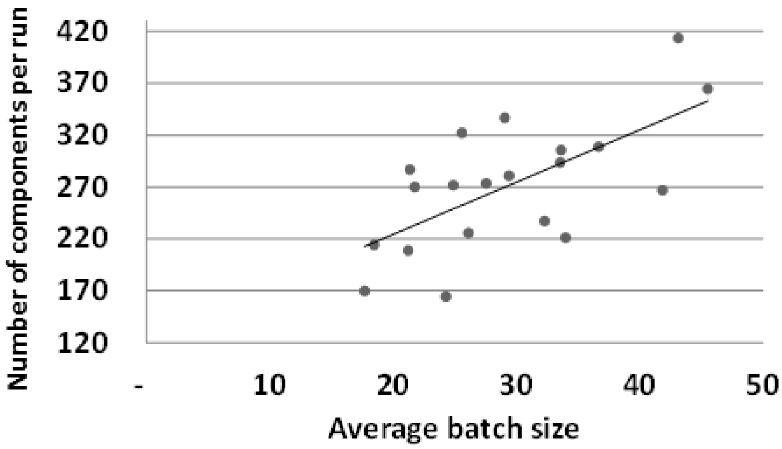

Figure 10 - Relation of lot size and production

The figure above (Figure 10) indicates how the machine utilization benefits from the increasing lot size for the specific production set up. The number of components produced per run is directly depended on the lot size. This implies that for the A components, where the production is high, the optimum lot size should be increased. By taking into account the changeover and set up time for the production of A and C components, the third scenario targets both on reducing the bottleneck forth machine and improving the capacity of the third stock. By applying the third scenario the realized benefits regarding the stock capacity optimization are illustrated in the following figure. The results indicate that by storing only A components 46% freed stock capacity can be achieved compared to the forecasted capacity requirements without implementing any changes to the current state.

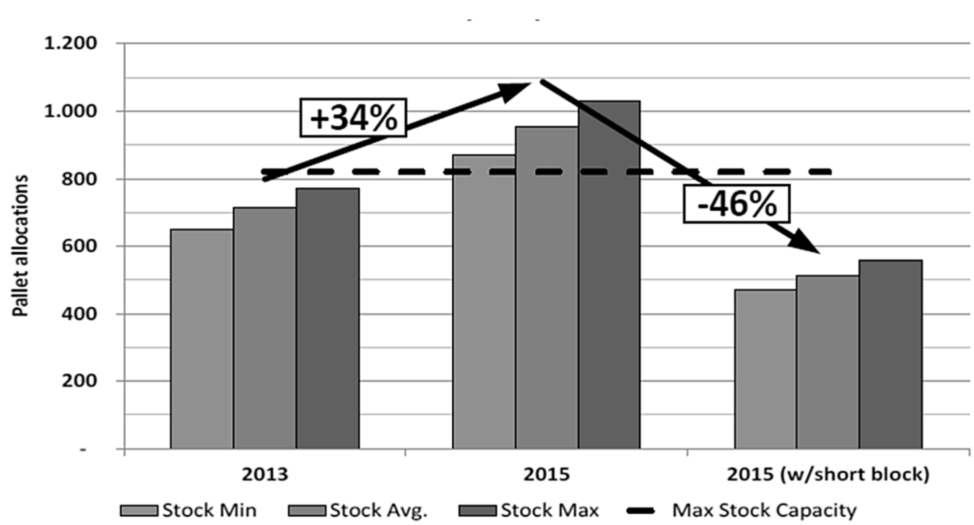

Figure 11 - Expected capacity improvement of third stock

5 Discussion

The results from the case study reveal that there is a relationship among the two-way component substitution and optimization of the process flow. All three suggested scenarios indicate that the reduction in the production of C components has a direct impact on the optimization of the stock capacity and elimination of the bottleneck machines. By combining the scenarios step wise, the final expected outcome for a two year period demonstrates that there is a significant improvement in the use of the stock capacity. The figures 7 and 9 illustrate the capacity utilization for the components kept in the second and third stock by comparing three states the current situation, the future state (in two years) without making any changes and the future state after implementing the suggested approach. The result shows that by substituting the C components with A, the average stock capacity will not exceed the maximum limits.

With reference to the cost of the suggested approaches, one cost aspect that should be taken into consideration is the extra scrap due to the size difference when evaluating the substitution of C components by A. On top of that, another cost is related to the purchase of the new machine required in the third scenario, for creating a separate production process for the C components. In order to evaluate the feasibility of that solution the cost of the shifts (standard and extra) and the cost of the new machine are calculated. The following tables demonstrate that the extra cost of the new process line is approximately 101.250 Euro, while the annual savings due to the elimination of the extra shifts due to the optimized process flow is approximately 254.250 Euro.

Table 4 - Annual extra cost for the new process line

	Weekday			Weekend		
	Night	Day	Evening	Night	Day	Evening
Hourly salary [€]	33	27	31	39	35	37
Hours per shift	7,5	7,5	7,5	7,5	7,5	7,5
Operators per shift	2	2	2	2	2	2
Extra shifts required	0	5	0	0	0	0
Weekly extra cost [€]	-	2.025	-	-	-	-
Annual extra cost [€]	-	101.250	-	-	-	-
Total annual extra cost [€]			**101.250**			

Table 5 - Annual savings from reduction of extra shifts

	Weekday			Weekend		
	Night	Day	Evening	Night	Day	Evening
Hourly salary [€]	33	27	31	39	35	37
Hours per shift	7,5	7,5	7,5	7,5	7,5	7,5
Operators per shift	2	2	2	2	2	2

Extra shifts required	0	0	0	- 4	-1	-4
Weekly extra cost [€]	-	-	-	-2.340	-525	-2.220
Annual extra cost [€]	-	-	-	-117.000	-26.250	-111.000
Total annual savings [€]				**254.250**		

6 Conclusions

With mass customization academia has addressed a growing demand for custom tailored products. From a solely mass production environment, manufacturers have been utilizing CTO strategies to realize higher product variety. In designing CTO production systems several considerations are made with regard to production flow, storage and machinery optimization. One way of balancing the right level of variety throughout production is by managing the complexity of the system.

With this study we have presented a practical framework for reducing the complexity level at different stages in production. An ABC categorization based on sales volumes has been used to distinguish between slow running and fast moving components, while BOM structures of final products have been analyzed to identify the sales volumes of components and modules. A two-way substitution has been used on different stages during production and its impact on lot sizing and capacity utilization for machinery and storage space has been discussed. The framework was tested on a case study, where a CTO manufacturer has been challenged with an increased customization demand and limited production capacity. Based on performed analysis, the impact of a number of complexity reduction scenarios was quantified in relation to total production cost and utilization.

The main limitation of this study is that it is based on a single case. This sets certain limitations regarding the generalizability of the research. For that reason the research group developed and discussed thoroughly the research design, so as to enable replication. At last, there is a limitation to the type of industry that this method can be applied to. The case company is from the manufacture environment and is considered to be highly representative. Regarding duration of the data collection, it can be extended in other cases, however for this specific example, as there is no seasonality of demand, data for one month on daily basis of the activities gives an overview of the average.

Future research should focus on testing the suggested method on more companies that fulfil the requirements. Additionally, the internal and external validity of the research method could be strengthened by conducting a longitudinal field study, where the expected outcome can be validated by the actual.

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ARTICLE I

Impact of product configuration systems on product profitability and costing accuracy

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Impact of product configuration systems on product profitability and costing accuracy

Abstract. This article aims at analyzing the impact of implementing a product configuration system (PCS) on the increased accuracy of the cost calculations and the increased profitability of the products. Companies that have implemented PCSs have achieved substantial benefits in terms of being more in control of their product assortment, making the right decisions in the sales phase and increasing sales of optimal products. These benefits should have an impact on the company's ability to make more accurate cost estimations in the sales phase, which can positively affect the products' profitability. However, previous studies have not addressed this relationship to a great extent. For that reason, a configure-to-order (CTO) manufacturing company was analyzed. A longitudinal field study was performed in which the accuracy of the cost calculations and the products' profitability were analyzed before and after a PCS was implemented. The comparison in the case study revealed that increased accuracy of the cost calculations in the sales phase and consequently increased profitability can be achieved by implementing a PCS.

Keywords: Product configuration system, Cost calculation accuracy, Product profitability, Benefits of product configuration systems, Longitudinal case study

1. Introduction

In today's business environment, companies are forced to offer customized solutions without compromising delivery time, quality and cost [1]. To respond to these challenges, mass customization strategies have received increasing attention over the years, from practitioners and researchers. Mass customization refers to the ability to make customized products and services that fit every customer through flexibility and integrations at cost similar to mass-produced products [2]. Utilizing product configuration systems (PCSs) is one of the key success factors in achieving the benefits of the mass customization approach [2,3].

PCSs are used to support design activities throughout the customization process, where a set of components and their connections are pre-defined and where constraints are used to prevent infeasible configurations [4]. Companies that have implemented PCSs have achieved numerous benefits such as shorter lead times, more on-time deliveries, improved quality, less rework and increased customer satisfaction [1,5–7]. In addition, the supportive function of the PCS enables improved decision making in the early phases of engineering and sales processes [8]. Furthermore, the system can be used as a tool that allows the salesperson to offer custom-tailored products within the boundaries of standard product architectures, thus giving companies the opportunity to be more in control of their product assortment [1]. It can be assumed that these benefits will have an impact on the company's ability to increase the accuracy of the cost calculations in the sales phase, which can positively affect the products' profitability.

However, the link between the implementation of a PCS and the effects on the company's ability to increase the accuracy of the cost calculations in the sales phase and consequently increase the products' profitability has not received much attention from researchers. Thus, the focus of this study is assessing the impact of implementing a PCS on a company's ability to make accurate cost calculations in the sales phase and products' profitability. Aiming to investigate these effects, the following propositions were developed:

Proposition 1 *The accuracy of the cost calculations in the sales phase is increased by utilizing a PCS.*

Proposition 2 *Product profitability is increased by utilizing a PCS.*

To test the propositions, a longitudinal field study was performed in a configure-to-order (CTO) company. In 2009, an analysis of product profitability and the accuracy of the cost calculations in the quotations generated in the sales phase was conducted. The results indicated that the performance of the sales processes could be significantly improved by implementing a PCS. That recommendation was adopted by the company; thus, a PCS was developed and implemented in 2011. Although the company has used the PCS since 2011, some salespersons still have not accepted the system and therefore generate quotations outside the PCS. This behavior provides an opportunity to compare quotations generated with the PCS and without the PCS over a 4-year period after the implementation. The results indicate that the quotations generated in the PCS have more accurate cost calculations, and consequently, the profitability of the products sold via the PCS is higher.

2. Literature review of the benefits of utilizing PCSs

In this section, the theoretical background of the present research is reported. To find relevant articles, a literature review was performed in the research area of PCSs. The focus of the literature review was identifying the main benefits and challenges of implementing and utilizing PCSs. Several research groups have conducted extensive studies in this field.

2.1. Benefits

First, the benefits identified by utilizing a PCS are discussed. As the focus of this study was to assess the impact of implementing a PCS, quantitative data were required. The results from the literature study are presented in Table 1. The benefits discussed in the literature are listed, and the articles discussing the benefits are listed in the second column. The last column specifies whether the impact of the utilization of a PCS was measured and shows quantitative data from the benefits identified.

Table 1. Benefits obtained from implementing PCSs.

Benefit	Authors	Measurement
Reduction in lead time for making specifications	[1,5,7,9–15]	From 5–6 days to 1 day [9] The real working time for preparing offers and production instructions is near zero [10] 75–99.9 % reduction in the quotation lead time [7] 15–25 days to 1–2 days [11]

Reduction in lead time for delivering the product	[10,13–17]	Delivery time reduced from 11–41 days to 1 day [10]
Saved work-hours	[1,9,11,14–18]	The engineering hours for creating quotations were reduced from 5 work-weeks to 1 to 2 work-days [11] Throughput cycle was reduced from 6 days to 1 day [18]
Increased quality of product information/specifications	[1,6,9,11–15,17–22]	Reduction to almost zero of errors in configurations released by the sales office [1] Increased level of correctness of product information to almost 100% [9] Specifications quality improved from 60% to 100% manufacturable [18]
Improved product quality	[20,23]	N/A
Improved on-time delivery	[1,9,24]	N/A
Increased employee productivity	[1,13,21]	N/A
Lower production costs	[10,20]	Fixed production costs were reduced by 50% and variable costs by 30% [10] Reduction from 30% to less than 2% in the number of assembly errors [10]
Improved efficiency in aftersales	[10]	Time for replacement was reduced from 5–6 hours to 20–30 minutes [10]
Improved knowledge management	[1,6,10,21,25]	N/A
Improved control of product variants	[1,9,19,24]	N/A
Reduced product lifecycle cost	[26]	PCS supporting the complete configuration process may reduce the configuration cost up to 60% over the product lifecycle [26]
Increased customer satisfaction	[20]	N/A
Improved customer relationships/communications	[1,9,12,19,21,25]	N/A

Summarizing the findings from the literature review, the implementation of a PCS provides various benefits to companies, in terms of resource reduction, decreased lead time, better communication with customers and improved product quality (Table 1).

There is a lack of empirical evidence that measured the impact of implementing PCSs on improved profitability and more accurate cost estimates. The present work contributes to the literature by providing a longitudinal field study that compared the economic performance of the products and the accuracy of the cost calculations before and 4 years after a PCS was implemented in an industrial manufacturing company.

2.2. Challenges of implementing a PCS

In this section, the literature focuses on the challenges and practical implications of implementing PCSs. The challenges refer not only to the scope of the PCS but also to the implementation and utilization of the system by employees and its acceptance as part of their daily work routine. The following table summarizes the main challenges identified in the literature.

Table 2. Challenges associated with utilizing PCSs.

Challenges	Authors
Supporting customers' needs in the configuration process	[26,27]
Product modeling and data acquisition	[1,6,9,26]
Errors in the configuration process	[6]
Documentation and maintenance configuration model	[6,9]
Change management	[1]

The implementation of PCSs are not free of challenges during the process. This is explained in the difficulties faced by the users and the developers of PCSs related to supporting customers' needs in the configuration process, product modeling and data acquisition, errors in the configuration process, documentation and maintenance and challenges regarding change management and acceptance of the system as part of the work procedures.

3. Research method

This research was conducted as a longitudinal field study, where the impact of implementing PCSs was analyzed, focusing on the accuracy of the cost calculations and profitability. The research was conducted as a collaboration between the Technical University of Denmark (DTU) and the case company over the 2009–2014 period and included multiple observations of the change process. The research team monitored the implementation and the impact of the PCS from the beginning until the PCS was fully integrated into the company's business processes. The company was selected as it is highly representative of medium-sized CTO companies that provide highly customized products and operate globally.

A longitudinal field study was selected as the research method for this work as this design allows the team to make real-time and in-depth observations of the change process and development in organizations [28,29] and specifically in this case, the process of implementing and utilizing a PCS over a 4-year period. Longitudinal field studies are a special type of case study in which the phenomenon is studied in its natural setting over time using multiple observations where the change process is observed as it unfolds in real time [30]. This type of study is most suitable when the aim is to explore new ground as the study design allows the researcher to be close enough to the studied phenomenon to discover the causal links among events and constructs [30].

Based on the nature and requirements of longitudinal field studies, this study was designed to investigate and analyze the existing problem of the lack of accuracy in cost calculations and product profitability. The unit of observation [31] was the different projects sold during the 2009–2014 period. The data required for the analysis included the estimated costs for each project sold and the actual cost. Data collection were collected about the salespersons and the quotations they generated at the company by using Excel spreadsheets and PCS. All data sets refer to 2009, before the PCS was implemented, and then to the 2011–2014 period when a PCS was used at the company. The data set for the analysis was extracted from the company's internal database and verified with specialists at the company.

4. Case study

4.1. Background of the case company

The case company analyzed in this study is a Scandinavian company in the building industry, which manufactures pre-made structural elements for buildings and provides installation services. The company is highly representative as a medium-sized company, which includes manufacturing, installation and maintenance in its business processes. In 2014, the company had around 100 employees and yearly turnover of approximately €17 million. In that year, the company sold 168 projects, and the average turnover per project was therefore €106,158. The company's product portfolio consists of six product families, of which five are standard products and one special.

In 2009, the process of generating quotations in the sales phase and the accuracy of the cost calculations were analyzed. The analysis revealed that the company's methods for accurately calculating costs were inadequate and affected the products' profitability. The results also indicated that the company's current procedure of using Excel spreadsheets to calculate the costs led to numerous errors, which were traced back to human mistakes. Based on this initial analysis, the company decided to invest €150,000 in order to develop a PCS to improve the process of generating quotations in the sales phase. The PCS used at the company was commercial configuration software, which builds on constraint propagation.

The PCS was developed from 2009 to 2010, and by the beginning of 2011, the company had developed a PCS able to handle most of the quotations in the sales phase. Only special products, which are categorized as non-standard solutions or engineered solutions, were not included in the system. Although the company developed and implemented a PCS to support the sales process, organizational resistance to using the system and changing current work procedures resulted in some salespersons still using the Excel spreadsheets to calculate costs for the quotations in the sales phase.

In this study, the impact of utilizing the PCS on the company's ability to make accurate price estimates for the quotations and product profitability was assessed. First, the company's overall performance is analyzed before the system was implemented in 2009 and 4 years after the implementation during the 2011–2014 period. Then the accuracy of the cost calculations and products' profitability in the quotations generated by using the Excel spreadsheets and the PCS were compared.

4.2. Analysis of the company's performance before and after implementation of the product configuration system

To compare the overall performance before the PCS was implemented (2009) and after the implementation (2011–2014), the contribution ratio (CR) is calculated for each project that was carried out at the company within the timeframe of this research. The CR is calculated as the ratio of the sales price and the contribution margin (CM), where the CM is the difference between the sales and the cost price. The cost prices of the projects are calculated as the sum of expenses, including construction site, subcontractors, materials and salaries. The formulas for the calculations of the CR and the CM are as follows [32]:

$$CR = CM \,/\, Sales\ Price \qquad (1)$$

$$CM = Sales\ Price - Cost\ Price \qquad (2)$$

The deviation in the CR is calculated as the actual CR (calculated after the project was completed when all expenses are known) minus the estimated CR (calculated in the sales phase when the cost is estimated). The formula for calculating the deviation of the CR as follows:

$$DEV_{CR} = CR_{actual} - CR_{estimated} \qquad (3)$$

If the real cost of the project is higher than the estimated cost, it results in negative deviation of the CR. Respectively, if the real cost of the project is less than the estimated, it results in positive deviation in the CR. Any deviation in the CR is something companies must be aware of. If the cost is overestimated, the company might lose the customer, and if the cost is underestimated, then revenue is lost.

The projects used for the comparison are from 2009, when only Excel spreadsheets were used to calculate the cost, until 2014. For the 2011–2014 period, the cost calculations were either performed in the PCS or by using Excel spreadsheets. Due to organizational resistance, not all salespersons used the PCS. In Table 3, the company's overall performance for 2009 and the 2011 to 2014 period is shown in terms of number of projects sold, the deviation in the CR and the average profitability.

Table 3. Overall analysis of the company's performance before the PCS was implemented (2009) and after (2011–2014).

Year	*No. of projects*	*Average* DEV_{CR}	*Average CR per project*
2009	55	–1.5%	25.0%
2011	117	–3.5%	27.2%
2012	90	–1.1%	28.5%
2013	116	–1.0%	28.2%
2014	168	–0.8%	29.0%

The analysis showed that the average CR steadily increased from 25.0% in 2009 to 29.0% in 2014. The implementation of the PCS was aimed to improve the company's CR by increasing the accuracy of the cost calculations in the quotations and thus the profitability of the projects. Furthermore, an additional functionality was included in the PCS that allowed the salespersons to set the desired CR for the project under question from an early stage of the sales process in order to make it easier to reach the goal.

Deviations in the CR also show positive improvements over the period as the average deviation was improved from –1.5% in 2009 to –0.8% in 2014. However, in 2011, the first year the PCS was utilized, the deviations in the CR increased considerably. This increase in deviations can be traced to the fact that the system had not been fully tested before the implementation and the users of the system lacked training. However, as the users became more experienced in using the system and errors were fixed, the PCS started providing valuable results.

This analysis indicates that the calculations are now more precise than before the implementation of the PCS and the company is moving closer to the targeted CR, and, consequently, the products' profitability is increasing. The results also highlight the importance of properly testing the system and training employees before the system is launched and fully functioning to avoid costly mistakes and to avoid resistance to using the system due to a lack of confidence.

4.3. Comparison of cost estimations and profitability between Excel and PCS

In this section, the yearly turnover, the CR of the projects and the deviations of the CR are analyzed and compared in terms of whether the initial quotation created during the sales phase was generated by the Excel spreadsheets or by the PCS. This comparison is possible because the PCS has not been accepted by all salespersons due to organizational resistance. Some still use Excel spreadsheets to generate quotations. The main reason is the lack of change management initiatives and the system being launched before it was fully tested, which resulted in some employees sticking to their old work habits [1].

4.3.1. The contribution to yearly turnover

To increase the understanding of to what extent the PCS is used at the company, the yearly turnover for the projects was compared based on whether the quotation was generated with the PCS or the Excel spreadsheets.

In 2011, the first year the PCS was utilized in the company, the turnover for the products' quotations generated with the PCS was higher than the ones created with Excel spreadsheets. However, in 2012 the turnover for the products' quotations generated by using Excel spreadsheets was higher. In the first year the system was running, the lack of training and errors in the system affected its functionality. However, in 2013, the quotations generated with the PCS contributed more to the yearly turnover, and in 2014, this difference increased even more, indicating that the salespersons were using the system to a greater extent. Fig. 1 shows the yearly turnover for the quotations created in Excel and by using the PCS.

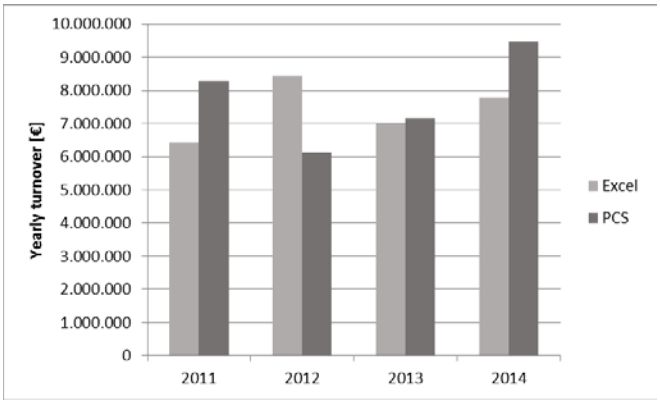

Fig. 1. Comparison of turnover generated for quotations created in Excel and PCS.

However, no clear trend was identified in the comparison. As can be seen in Fig. 1, in 2012, the projects handled by the salespersons with Excel spreadsheets contributed more to the company's turnover although the PCS had already been implemented. Some salespersons were reluctant to use the PCS in their working processes, as they still used Excel spreadsheets for calculating costs and generating quotations. Second, lack of training and errors in the system in 2011 might have given some salespersons the wrong impression of the usability of the system, which resulted in them not using the PCS in the following year. In detail, in 2011, 52% of the projects were handled with Excel spreadsheets to generate quotations, which corresponds to 47 out of 90 projects. The 2011–2012 period was the initial introduction of the PCS at the company, and the PCS did not include all products at that point; therefore, utilization was by definition limited. During the trial period, the turnover contributed by the projects handled in Excel was higher than the turnover from the projects handled in the PCS, but this changed significantly in the following 2 years. Thus, in the 2013–2014 period, when the company took greater advantage of the PCS, and its utilization was strongly established, the turnover of the projects worked out by using the PCS outnumbered the ones generated with Excel spreadsheets.

Overall, by comparing the yearly turnover of the projects handled through Excel spreadsheets and the PCS, no clear conclusion was reached. Thus, the next step of the analysis focused on identifying and comparing the CR for products sold via Excel and PCS.

4.3.2. Comparison of project profitability

To compare the profitability of the projects, the CR was used as it represents the ratio between sales prices and the CM, and a good indicator of project profitability. As previously explained, the company's goal for all projects is a CR of 30%, as a result of a strategic decision made in 2009 to increase the CR from 25% to 30%. The implementation of the PCS was aimed to reach the targeted CR of 30% for the projects. The analysis of the overall company's performance (Table 3) showed how the CR has increased since 2009. However, to confirm that this can be traced to the implementation of the PCS, a comparison of the CR of the quotations made by using the PCS and Excel spreadsheets was performed. In Fig. 2, the actual CR (calculated based on the actual cost of the projects) is illustrated for the quotations created with the PCS and Excel.

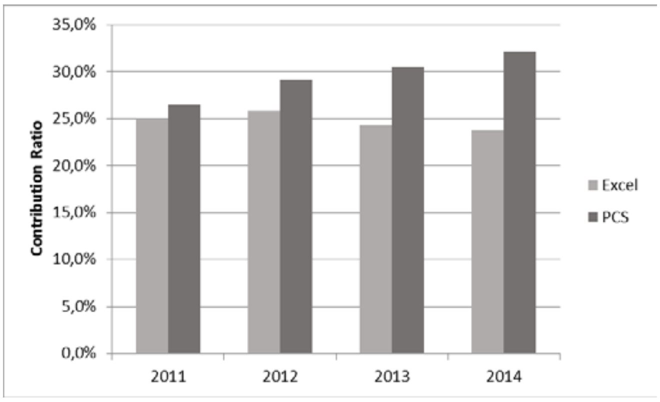

Fig. 2. Comparison of CR for salespersons using Excel and PCS.

Salespersons who used the PCS contributed a higher CR than those who used Excel spreadsheets. Furthermore, the gap in the CR increased between the salespersons who used the Excel spreadsheets and those who used the PCS. In 2014, the average CR was 29.0%; salespersons who used the PCS had an average CR of 32.1% while salespersons who used Excel spreadsheets had 23.8%. In other words, the salespersons who used the PCS achieved a goal of 30%. The increasing gap between the CR for the quotations generated in the two systems can also be explained as a result of the increased utilization of the PCS and the company's effort to update prices in the PCS instead of the Excel spreadsheets. Finally, special products were not included in the PCS; therefore, to calculate the costs, Excel spreadsheets were always used. Although those products were not included in the calculations for the quotations made in Excel presented in Fig. 2, they did not contribute significantly to the average CR. For example, for 2014 they affected the CR for the quotations created in Excel by only 0.2%. Therefore, the lower CR cannot be traced to special orders. This result confirms the second proposition formulated in this study: Product profitability increased when the projects are handled through a PCS.

4.3.3. Comparison of the accuracy of the cost calculations

To compare the accuracy of the cost calculations generated in the PCS and Excel spreadsheets, the DEV_{CR} is calculated. The results are shown in Fig. 3.

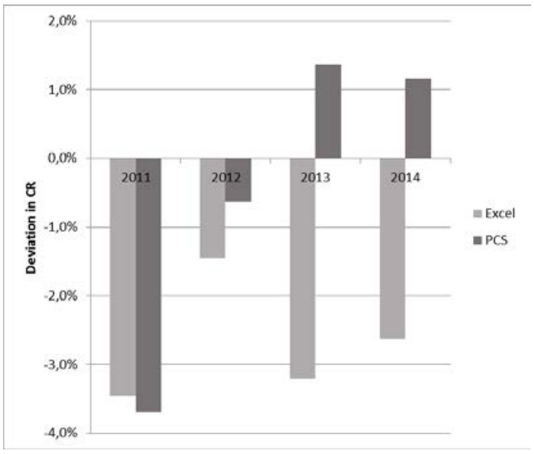

Fig. 3. Comparison of deviations in CR for salespersons who used Excel and PCS.

The CR showed less deviation for the products for which salespersons used the PCS than the CR for the products for which salespersons used Excel spreadsheets, with the exception of 2011. The deviation in the CR for the PCS in 2011 can be explained as a result of insufficient testing and a lack of training, which affected the performance in the first year after the implementation. In the following year, 2012, there was a significant reduction in deviations for quotations created via Excel spreadsheets and, mainly, for the ones created through the PCS. Moreover, in 2013 and 2014, the deviations in the quotations created by the PCS were positive (1.4% and 1.2%, respectively), while the deviations for the cost calculations generated with the Excel spreadsheets were negative and still quite high (–3.2% and –2.6%). Another possible explanation for the increasing gap between the CRs is the more complete cost calculations via the PCS than Excel spreadsheets. All parts required for every product were included in the PCS, while when the cost estimate was created in Excel spreadsheets, the salesperson might forget to include all of them. As a result, the estimated cost did not include all required parts and was lower than the actual cost, which led to the negative deviation in the CR. The analysis of the performance of the salespersons who used Excel and the PCS therefore indicates that the PCS affected the accuracy of the cost estimates and the CR positively, which supports proposition 1.

5. Discussion

This work focused on measuring the benefits of implementing a PCS in a CTO manufacturing company. To measure the benefits, the CRs of the products handled in Excel and the PCS were calculated and compared. The comparison revealed that the CR of the products handled via the PCS was higher than the ones in Excel. Taking into account the increase in the CR from 25% to 29%, which is equivalent to €654,000 per year, and the cost of the development of the PCS was €150,000, the annual return on investment (ROI) was 336%. In addition, the accuracy of the quotations generated by the PCS was higher than those generated in Excel.

Regarding the salespersons who were still using the Excel spreadsheets while the PCS was implemented, reasons similar to those identified in the literature review were reported [1,6,9,26]. In detail, the most experienced salespeople in the company were those who were still using Excel in 2014 to generate quotations. They stated that the PCS did not add value to their daily routine as long as it was not updated for the user interface and functionalities and included all relevant products. Therefore, the PCS had to be upgraded with all functionalities in order to be fully accepted and adopted by all employees and enable the company to seize the full benefits of the PCS.

To improve the company's general performance, several factors were identified, which could help the company reduce even further the deviations in the CR and increase the overall profitability of the products. For instance, the company intends to implement a checklist at the end of each configuration in order to ensure that all required information is gathered during the sales phase and is up-to-date. Implementing the checklist will reduce the number of errors made during the sales process. Furthermore, the company plans to increase standardization in their product range, by moving further to modular-based product designs. Regarding the further development of the PCS, the company has decided to invest €140,000 to include more products. Finally, to implement an organizational change [1] and boost utilization of the PCS, all new employees are trained to use only the PCS; thus, the Excel spreadsheets will become obsolete.

6. Conclusions

The aim of this case study was to measure the impact of utilizing a PCS on product profitability and the accuracy of cost estimates. The study resulted in significant improvements in the CR of products sold through the PCS due to the accuracy of the cost calculations. The results from the longitudinal case study confirmed the propositions. In detail, the improved accuracy of the cost calculations and the increased profitability of the products sold via the PCS were demonstrated. The quotations generated by the PCS and Excel for the 2011 to 2014 period were compared, when the PCS had been implemented and was used to its full potential. The analysis led to the conclusion that the contribution of the PCS is noteworthy, as the performance of the products included in the PCS improved in terms of more accurate cost estimates and improved profitability (propositions 1 and 2). This could be explained by the fact that the data used in the PCS is updated and all possible solutions are validated before making an offer, the generated quotations include fewer errors and more accurate price estimates than the quotations for products not included in the PCS. However, this study also highlights the importance of fully testing a PCS before making it operational. To this end, as can be seen from the results, the implementation had a negative impact in the first year due to insufficient testing. In addition, the challenges of scoping and utilizing a PCS are discussed in the literature and the empirical evidence here.

This research is the first step in exploring the impact of a configurator on product profitability. Thus, more cases need to be examined, to compare the profitability between projects going through the PCS and outside it and salespersons' performance before and after the implementation of a PCS. By examining more cases, a deeper understanding can be gained, and a more detailed explanation of the correlation between the configuration tools and product profitability can be provided. In this paper, empirical evidence was provided by only one case company. However, the impact registered in this company indicates that there could be significant impacts from implementing a PCS, which have not been previously discussed in the literature. The increase in the CR of the products is important, and the PCS brought significant value to the company. Therefore, this requires further research and additional cases to confirm the underlying correlation between a PCS and an increase in profitability. Future research should include investigation of other benefits of utilizing a PCS, such as its impact on an increase on sales.

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ARTICLE J

Product configuration system and its impact on product's life cycle complexity

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Abstract – **The purpose of this paper is to identify areas throughout a product's lifecycle processes where complexity can be reduced by implementing a product configuration system (PCS). As discussed in the literature, several benefits are realized by using a PCS in terms of product and process standardization. This also leads to control and reduce of complexity both in products and processes. To this end, this research attempts to quantify and assess these benefits and is supported by empirical evidence. A case study of an engineering company is used and the results indicate significant improvements for the company in several life cycle processes.**

Keywords – **Complexity, Engineer-to-order companies Product configuration system (PCS), Product life cycle**

I. INTRODUCTION

This paper aims to explore the overall impact on complexity reduction throughout the products' life cycle by implementing a product configuration system (PCS) in the early sales phase (Fig. 1). The literature describes various benefits that can be gained from implementing PCSs, however the connection between those benefits and the effects on complexity reduction in the different phases of the products' life cycles has not been explored to full extent. This research focuses on engineer-to-order (ETO) companies; companies considered are producing and selling complex and highly engineered products, such as cement or chemical factories, oilrigs etc.

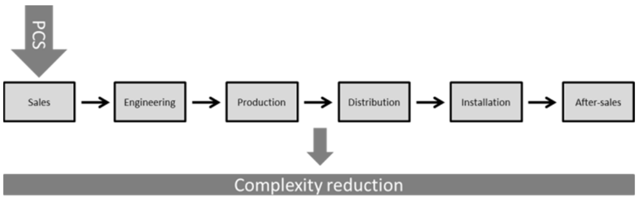

Fig. 1 - Impact of implementing PCSs in the sales process on the different phases of the product's life cycle.

PCS are widely used on products and services. With reference to products, they are utilized at different phases of a product's life cycle (design and engineering, sales, manufacturing, installation and after-sales) and various benefits have been discussed in the literature regarding lead times, quality, optimization of products and services etc. [1, 2]. The complexity of handling information for a product increases the more complex and highly engineered the product is [3].

Regarding complexity in a manufacturing company, it can be identified in products, processes and organization [4], and it lies upon each of those aspects but also in their interrelationships [5, 6]. There are several factors discussed in the literature related to complexity of products' life cycle [7].

Benefits of utilizing a PCS can be realized in the different life cycle processes and have an impact on several cost areas within a manufacturing company. As a result this research combines the fields of PCS and complexity, by assessing how product's life cycle complexity can be reduced by the utilization of a PCS. A case study is used to supplement this research.

II. LITERATURE REVIEW

A. *Benefits from using PCSs*

In this section the benefits from the utilization of a PCS identified in the literature are discussed and grouped according to different lifecycle processes.

PCSs have been implemented widely to support the specification process for the customized products and guide the sales process [8]–[10]. The benefits from applying PCSs can be described in terms of shorter-lead time and improved quality of the product's specifications, reduced resource consumption and increased customer satisfaction [11]. For that reason, less rework and less iterations are required, as the quality and the accuracy of quotations are increased [12]. Furthermore, PCSs can be used as tools that support sales persons to offer customized products within the boundaries of standard product architectures and thereby enable companies to be more in control of their product assortment [2, 13].

In order to achieve the benefits from a mass customization approach, utilization of PCSs and standardization of the product's architecture are considered as the main enablers [14, 15]. The growing product variety at the companies has led to an increasing complexity of products and processes and to the need of better coordination of the way product specifications are performed [16]. PCS are used to support the product configuration processes, which consist of a set of activates that involves gathering information from customers and generation of all required product specifications [2, 16]. In PCSs a set of components along with their connections are pre-defined and where constrains are used to prevent infeasible configurations [17].

Companies utilizing PCSs have achieved increased ability to manage product variety, improved product quality, simplification of the customer order process and complexity reduction [2], [18]–[20]. Furthermore, preservation of knowledge, use of fewer resources, optimization of products designs, less routine work, improved certainty of delivery, reduced time for training new employees and increased customer satisfaction [11], [16], [21]–[24] have been reported in the literature as benefits achieved via the use of a PCS. In addition, when the complete configuration process is supported by a PCS, the configuration cost may reduce up to 60% over the product lifecycle [13]. On the other hand, by utilizing a PCS companies can increase sales of more standardized products and become more in control of their product range, which can lead to higher efficiency, improved quality, and reduce the product complexity [2].

The following table demonstrates these benefits according to the different life cycle processes.

TABLE I
SUMMARY OF PCS's BENEFITS ON LIFE CYCLE PROCESSES

Life cycle process	Benefit
Sales	Reduction in quotation lead time [25] Increase customer satisfaction [26] Improved communication and relationship with customers [2], [9], [10], [27]–[29] Improved control of product portfolio [2], [27], [29], [30]
Engineering	Reduction in lead time for preparing specifications [31] Increased quality of specifications (less errors) [32]
Production	Reduction in work hours [12] [33] Reduction in hours making production instructions [31] Improved quality and number of specifications that can be used directly without iterations [16], [33]
Distribution	Reduction in delivery time [31] Improved on-time delivery [2], [27], [30]
Installation	Reduction in number of errors [31]
After-sales	Improved efficiency [31]

B. Complexity in product lifecycle processes

Complexity is realized both in products and processes of the entire life cycle. Five areas of complexity are identified by [34]: product design, procurement, manufacturing process, product range, and distribution. Reference [35] distinguishes complexity cost between those that occur only once, at the introduction of the new variant, and those that re-occur during the entire lifecycle of the product. Reference [36] identifies and calculates the complexity costs for the business processes, by using a case study in the automobile manufacturing. The research concludes with the cost structure and the break-down of complexity costs to different processes. 15-20% of the total costs are considered as complexity costs, which are allocated to several business processes, such as inventory, production, logistics and sales.

The methods suggested reducing product complexity focus on increasing the overview and transparency of the product assortment [37] and improve product standardization [38]. Regarding methods for reduction of process complexity, optimization of the different lifecycle processes is discussed, in areas such as supplier-customer relationship [39], manufacturing process [40], production process [41], [42] and distribution [43]. Reference [44] suggests mass customization as a strategy for eliminating complexity caused by increasing variation in product architecture, inventory and order taking process.

C. Bridging the gap between complexity and PCS

Based on the literature discussed above, it can be concluded that PCS and complexity reduction are highly related topics within a manufacturing company. By implementing a PCS improved standardization of products and processes is achieved. Yet, through increased standardization complexity is also reduced in both the products and the life cycle processes. Hence, the direct impact of implementing a PCS on complexity is considered to be a great interest.

Therefore, this research studies the impact from implementing a PCS in the early sales phase on the complexity reduction through the entire life cycle of a product. In the early sales phase the most important decisions are taken and the characteristics of the products are determined. Based on the above, the following proposition is developed and tested in a case study.

Proposition 1 (P): Cost reduction is achieved through reducing complexity of a product's lifecycle processes by the use of a PCS.

The main proposition is divided into two parts, in order to be tested in the case study. The first one, studies the effect of reusing parts of completed projects to new ones. Then, a generalization of this concept is examined through the implementation of a PCS.

Proposition 1a (P1a): If it possible to reuse parts of the design of new projects from completed ones, then a significant reduction of costs of engineering, production and repairs after installation due to defects is achieved.

Proposition 1b (P1b): Application of PCS in the sales phase and increase of modular product range may lead to more standardized products and benefits proved in *P1a* indicate the scale of possible savings.

III. CASE STUDY

A. Introduction and Problem analysis

The company selected as a case study in order to test the suggested proposition is an ETO manufacturer in the oil and gas industry. The company provides single equipment and complete systems and services and it operates worldwide. This specific company is chosen as a case study to be further investigated as it is considered to be highly representative in the engineering industry, so replication of the research could be ensured.

Data collection includes the cost for all the complete systems (projects) and single equipment (products) sold over a four-year period. The unit of analysis is the number of sales including projects and products. The related costs refer to the different phases of the products lifecycle, such as sales, engineering, production, distribution, installation and after-sales. Data were obtained through the company's internal database and verified by specialists within the company (project managers).

In detail, the different cost categories that are taken into consideration for the analysis are the following: inventory, material, engineering, production, assembly, outsourced parts and services, installation. The inventory cost and production account for more than 50% of the total cost both for projects and single products. The cost of engineering for the projects varies from 10% to 20% of the total cost, while for single products is 6%. These two cost groups account for the largest share of the total cost.

In the four-year time period, the company sold 12 projects and 193 single products. Based on the data acquired, the revenue for the projects is 743,5 m€ and for the single products 46,5 m€. Respectively, the costs are 758,7 m€ for the projects and 30,9 m€ for the single products. It can be seen from the numbers above that even though the projects create higher revenue compared to the sales of single equipment, the related costs are even higher, resulting in loss for the company. Furthermore, for the projects sold a deviation is identified between the estimated cost and revenue at the beginning of the project, when the budget is calculated, and the actual ones, when the project is finished.

These deviations can be due to external factors, such as currency, fluctuation on material price and labor cost. However, there are internal factors that also influence the increase of the estimated cost and revenue, and they need to be further investigated.

To this end, an area of interest identified during the analysis of the financial performance of the projects is the reduction of cost through repetition. When a project is re-produced based on an existing one, several cost categories are identified to have noteworthy reductions.

Engineering costs, which are calculated based on the hours spent for each project or product, seem to benefit from re-using existing documentation. The following figure illustrates the amount of hours spent on engineering for the pioneer project and for the projects reusing parts.

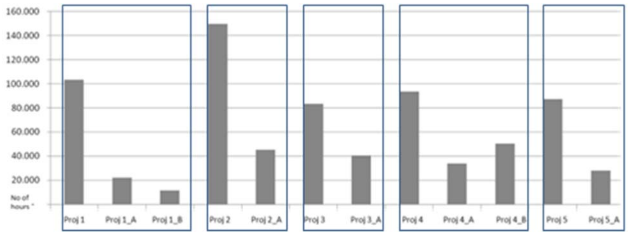

Fig. 2. No of engineering hours spent on original projects and projects reusing parts.

A trend can be seen, that for the projects that are replicated the engineering cost is always reduced. Only Proj 4_B, which is the second project created based on the initial Proj 4, is an outlier. This is explained by the fact that Proj 4_B is only partly a copy of the initial project.

The figure below illustrates a similar effect on the production costs through reusability of existing material, such as drawings, instructions and documentation.

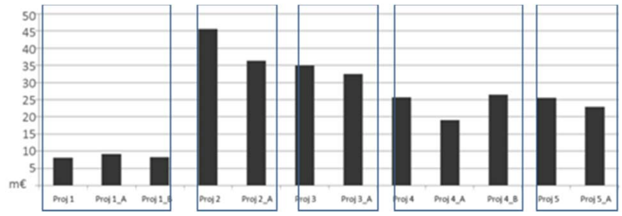

Fig. 3. Production costs of original projects and projects reusing parts.

Engineering and production costs account for more than 50% of the total cost, as explained before. As a result, these savings through re-usability and standardization of the processes could have a significant impact on the overall financial performance of the company.

Another cost area that showed significant savings in that aspect is the repairs after installation due to defects. The results can be seen in the following figure.

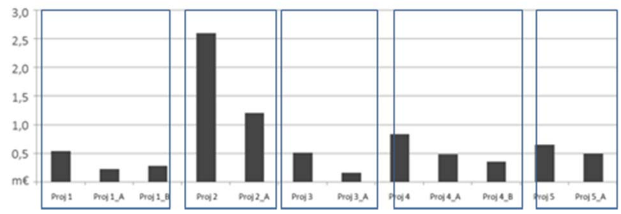

Fig. 4. Costs of repairs after installation due to defects for original projects and projects reusing parts.

This trend of cost reduction through reusability is also identified in other costs which are related to different life cycle processes, such as the revisions of drawings and changes on the drawings, outsourced production equipment and commissioning. The results from the figures above verify proposition 1a.

Nevertheless, deviations on the estimated costs and actual ones for the projects which are reusing parts is reported. Even though there is a significant reduction in various cost areas, still the company did not managed to reduce the cost to the desirable limit. And that is the reason why there is no profit gained for the sales of the projects.

B. Results and Methods for Improvement

Based on the analysis of the financial performance of the company two main areas of potential improvement can be identified as discussed in the literature [38], [45]; standardization and reusability. In order to achieve these improvements, firstly, the company should increase the standardization of the product portfolio. By changing or adjusting the products' architecture, the company can seize the benefits of complexity reduction in the product assortment. Then, the standardization of the processes and the increase in material reusability can be achieved by implementing a PCS. Through the utilization of a PCS both product and process complexity can be reduced and this would have a direct effect of cost savings.

In order to assess the potential benefits of suggested method, a sensitivity analysis is performed on the main cost areas, as they were identified in the section above. The table below indicates the main cost areas and the scenarios developed to estimate the potential benefits.

TABLE II
ASSESSMENT SCENARIOS

Cost areas	Conservative	Realistic	Optimistic
Engineering hours	5%	10%	20%
Production costs	10%	20%	30%
Repairs after installation	30%	50%	80%

The scenarios are implemented to both the 12 projects and the 193 single products, which were also used for the analysis of above. The results of the sensitivity analysis are illustrated in the following table.

TABLE III
SCALE OF SAVINGS FOR THE SCENARIOS

Cost areas	Conservative	Realistic	Optimistic
Engineering hours [m€]	1,9	3,8	7,6
Production costs [m€]	33,6	67,2	100,8
Repairs after installation [m€]	2,8	4,5	7,1
Total [m€]	38,3	75,5	115,5

As it can be seen from Table III the potential savings in all the cost groups taking into consideration in the sensitivity analysis vary from 38,3 m€ for the conservative approach to 115,5 m€ for the optimistic scenario. These results showing significant potential for further cost reductions and the scale of possible savings, so they are aligned with the proposition 1b.

IV. DISCUSSION AND CONCLUSION

The scope of this study is to identify how the costs vary between different projects in an engineering company with particular focus on the effect of having more standardized product designs in the projects. The study reveals that when projects are repeated using similar equipment from a previous project then the cost will be significantly reduced.

Literature claims that use of modularization and configuration systems would lead to more standardized projects and thus to cost reduction. This study reveals that if it is possible to base an engineering project on previously designed parts then it is possible to obtain some very significant savings. This indicates the scale of potential savings that may be obtained by applying modularization of the products in the projects and by using product configuration systems for actually selling these more standardized solutions.

Additional examples from engineering companies have to be added in the future in order to ensure generalizability of the suggested method.

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